ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

PhD THESIS

Siamak BAZAATI

OPTIMAL CONSTRUCTION SITE LAYOUT CONSIDERING SAFETY AND COST ASPECTS

DEPARTMENT OF CIVIL ENGINEERING

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ÇUKUROVA UNIVERSITY
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DEPARTMENT OF CIVIL ENGINEERING

We certify that the thesis titled above was reviewed and approved for the award of degree of the Doctor of Philosophy by the board of jury on 01/09/2016.

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ABSTRACT

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Distance and safety are two essential factors while designing a good construction site layout planning (CSLP). In the past, studies always considered CSLP from the treated a single objective optimization problem. This study offers the development of a site layout planning model that is capable of minimizing construction safety risk and minimizing the total distance of interaction on the site, simultaneously. For this purpose, this study uses the multi-objective Particle swarm optimization algorithms (MO-PSOs).

The present model was developed in five main phases:

(1) Investigate and develop objective criteria to enable minimizing construction safety risk of crane operations; (2) Investigate and develop objective criteria to enable minimizing the total distance of interaction; (3) Modeling the site layout practical optimization constraints; (4) Implementing the model as a multi-objective particle swarm optimization algorithm application; and (5) Evaluating and verifying performance of the model by the grid search method. An application case study of a residential building project is presented to demonstrate the benefits of the usage of the model.

Key Words: Optimization, Construction site layout planning , Multi-objective particle swarm optimization.

ÖZ

DOKTORA TEZİ

İNŞAAT PROJELERİNDE ŞANTIYE YERLEŞMESİNİ GÜVENLİK VE FIYAT BAKIMINDAN OPTIMUM YAPMAK

Siamak BAZAATI

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İnşaat şantiyelerinde iyi bir şantiye düzeni planlaması tasarlanırken, mesafe ve güvenlik iki temel faktördür. Bu çalışma eş zamanlı olarak şantiyedeki güvenlik riski ve tesisler arasında seyahat mesafelerini en aza indirgeme yeteneği olan bir şantiye düzeni planlama modeli sunmaktadır. Bu amaç doğrultusunda, bu çalışmada Çok Amaçlı Parçacık Sürü Optimizasyon Algoritması (ÇA-PSO) kullanılmıştır. Mevcut model beş temel aşamadan oluşmaktadır: 1-İnşaat işlerinde güvenlik riski üzerinde doğrudan etkisi olan değişkenleri belirlemek ve modellemek. 2- Şantiyelerde kaynakların seyahat mesafelerini doğrudan etkileyen değişkenleri bulmak ve modellemek. 3- Bu tarz karakteristik ve pratik optimizasyon problemlerinin kısıtlamalarını keşfetmek ve modellemek. 4. Modeli Çok Amaçlı Parçacık Sürü Optimizasyonu Algoritması olarak uygulamak. 5. Modelin değerlendirilmesi. Bir konut projesinin vaka çalışması modelin uygulamade kullanımının faydalarını göstermek için sunulmuştur.

Anahtar Kelimeler: Optimizasyon**,** Şantiye düzeni planlaması, Çok amaçlı parçacık sürü optimizasyon algoritması

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LIST OF ABBREVIATIONS AND NOMENCLATURE

A	: Absolutely necessary
ACO	: Ant Colony Optimization
DOE	: Design of Experiment approach
d_{ij}	: Distance between facilities i and j
distance	: Distance between facility i and tower crane
GA	: Genetic Algorithms
GIS	: Geographic information systems
GUI	: Graphical user interfaces
H	: Height of the tower crane
i	: Temporary facility identity
I	: Important
it size	: Iterations sizes
J	: Length of the tower crane
L	: Low
LX	: The left boundary of the site space.
LY	: The lower boundary of the site space.
M	: Medium
m	: Number of experts.
MOO	: Multi-objective optimization
MO-PSO	: Multi-objective Particle swarm optimization algorithms
MODM	: Multi-objective decision making
n	: Number of temporary facilities.
NP-hard	: Non-deterministic Polynomial-time hard
O	: Ordinary closeness
OSHA	: Occupational safety and health administration
P	: Probability of an accident
P(distance)	: the function that determines the magnitude of the probability of an accident (p)
pop size	: Population sizes

PSO	: Particle swarm optimization algorithms
RM	: Risk Magnitude
RM_i	: risk magnitude (RM) of the facility i due to its possition with respect to the tower crane.
RM_{Ai}	: Presents the fatality & injury risks related with possible strucks on the temporary facility i by tower crane loads (The values were obtained from the results of the survey applied to the experts.)
RM_{Bi}	: Presents the fatality & injury risks related with possible load falls on the temporary facility i from the tower crane (The values were obtained from the results of the survey applied to the experts.)
RM_{Ci}	: Presents the fatality & injury risks related to crane collapses on the temporary facility i (The values were obtained from the results of the survey applied to the experts.)
RS_{Tfij}	: Illustrates the risk severity by the tower crane for temporary facilitiy i expressed by the expert j then changed into a constant depending Zeng et al.2007
rep size	: Repository size
SR	: Safety risk
U	: Unimportant
UX	: The right boundary of the site space
UY	: The upper boundary of the site space
VL	: Very low
VH	: Very high
W_{ij}	: Proximity weights for various facilities relationships
W_{Ej}	: Introduces the weight of risk expert j
X	: Undesirable
X_i, Y_i	: Coordinates of the center of gravity of facility I
X_j, Y_j	: Coordinates of the center of gravity of facility j
δ	: Gap between facilities and boundary in the X,Y direction.

1. INTRODUCTION

Site layout planning is one of the significant tasks of the site management. The large projects which involve the high number of manpower, subcontractors and equipment involved could result in extensive time loss and cost overruns in the absence of effective and systematic approach to site planning. Site layout and location of temporary facilities which is comprehensively planned can enhance the management by reducing travel time, allowed time and increasing employee morale by ensuring better and safer working environment. The site layout planning problems were thoroughly discussed in this paper as considering its importance (Harris, 1989). Construction site layout planning comprises determining, sizing and placing of the temporary facilities in the boundaries of the construction site. Many factors such as project type, scale, design, location, and organization of construction work are essential for the temporary facilities and their fields (Hedley, 1983).

When general construction site layout is designed, the structure to be constructed should be in relation to General Construction Site Layout Planning, the arrangement of temporary structures, yards, stores, etc., for instance, location of structures to be built; directions of access routes; location of the main pieces of equipment; location of stores, deposits; temporary building, offices.

A high-quality construction site layout planning (CSLP) is very important to increase the productivity of a construction project. Because of its complexity, construction site layout planning is taken into consideration as ‘NP-hard’ problem (Non-deterministic Polynomial-time hard) (Lien et al., 2012). Significant research advancement has been accomplished in the area of optimizing site layout planning, guiding to a number of models that using a variety of approaches comprising artificial intelligence (Tommelein et al.,1992), annealed neural networks (Yeh, 1995), dynamic layout planning (Tommelein and Zouein, 1993), geographic information systems (GIS) (Cheng and Connor, 1996), and genetic algorithms (Li and Love, 1998). The power of the recent meta-heuristic algorithms depending on swarm intelligence have been proven in finding the solution of that type of optimization problems (Saka and Dogan, 2012). This has led researchers to adopt these modern meta-heuristic algorithms to determine the solution of their proposed CSLP models. Although these models have great contributions, they were still focused on diminishing the travel cost of resources on the site. Thus, they are insufficient to consider and maximize construction safety. Even though these models are competent to (1) adapt to a variety of construction projects; (2) an extensive multi-objective optimization module to give practical automated support for construction planners who need to optimize the design of site layout plans, deficiencies of them also were revealed by the literature review.

However, a suitable site layout should be helpful for site planners to decrease costs and save the safety involved. Thus, the current study aims to develop a site layout planning model which would maximize construction safety (determinant safety zone and forbidden area) while minimizing the construction distance. The current study also showed that presented models that are suitable for as follow;

1. Fitting any user-defined construction projects (for this purpose the proposed model is affected the results gained through the survey of risk experts connected with the target project site)
2. Recommended a comprehensive multi-objective optimization module that optimizes and combines the overall impact of site layout planning on minimizing the risk of Crane Operations accidents happened to enhance the safety level, and minimize the total distance of interaction, the major target of the present system is to provide practical automated support for construction planners who want to optimize the design of site layout plans;
3. Using the grid search method for model assessment and results from affirmation.

The limitations of the current model are only convenient for quadrilateral construction sites and for one tower crane.

The organization of the main research tasks of the present thesis is described as follows:

Chapter 2 presents a detailed literature review in examining and analyzing the practices in planning the location of temporary facilities on construction site

Chapter 3 presents the development of a site layout planning model that is capable of minimizing construction safety risk and minimizing the total distance of interaction on the site, simultaneously.

Chapter 4 was divided into three main sections, as in following:

1. Multi-objective site layout optimization system
2. Application example
3. Model evaluation and results verification

Chapter 5 presents the conclusions and recommended future research of the present study.

2. PRELIMINARY WORK

The reviewed literature in examining and analyzing the practices in planning the location of temporary facilities on construction sites is summarized and organized in this chapter.

The diverse methodologies used in the literature to perform site layout planning tasks are discussed in the following sections.

2.1. Site Layout Planning by Genetic Algorithms

Li and Love (1998) offered a GA model to assign a set of facilities to a group of predetermined potential locations. The model presumes that each of the predetermined locations is adequate for accommodating the largest among the facilities. Permutation was used in this study as a representation scheme. In substance, this novel study investigated the effect of population size on the convergence of the GA system. According to the experiments, GA system approached earlier to the medium size of the population.

Hegazy and Elbeltagi (1999) introduced a genetic-algorithm-based model for site layout planning. This model has three favorable characteristics: (1) It is valid for any user-defined site shape; (2) it clarifies choice of the users in the relative closeness among the facilities; (3) it combines a genetic algorithm procedure to investigate the optimal layout in a manner that mimics natural evolution. In brief, the study and experiment about the effect of population size on the convergence of the GA system showed that the GA system converged earlier with the largest size of the population.

Harmanani et al. (2000) practiced an evolutionary algorithm using weights to model transportation costs between facilities to optimize the solution of site layout problems. The designed system deals with sites which are characterized by geometric limitations between relative positions of facilities on site. The designed system deals with sites which are characterized by geometric limitations between relative positions of facilities on site. It is possible to be 2- dimensional geometric limitations on the relative positions of the facilities; minimum and maximum distance; orientation (N, E, W, S); and non-overlap restrictions. This algorithm has two key features which are (1) the use in a multitude of different GA operators to change positions of the objects around the site, and (2) preservation “bad” chromosomes (chromosomes referring the partial layout solutions) in each generation to assist the evolution process to approach to a global optimum. Limitations of the system are static problems and rectangular shaped facilities with fixed dimensions and their orientations can be 0 or 90 degrees. Occasionally, the system can create the partial layout solutions, owing to excluding some blocks that are not optimized after reaching a threshold limit value (100 cycles). As long as the total-objects-to-site-area ratio does not go beyond 60%, the algorithm returns close to optimal solutions. In the case of problems with a higher total-objects-to-site-area ratio, the algorithm is not successful to return possible solutions. An approximately linear relationship between computational time and the number of layout facilities is shown in the study.

Tawfik and Fernando (2001) suggested a parallel genetic algorithm, hence locations of space on the sites are optimized by using a single function that considers the cost and safety of construction operations. The system focused on the safety criterion by identifying hazards zones of site spaces such as cranes, vehicles, and equipment as well as penalizing the temporary facilities that lie within these zones by increasing their associated cost function. A genetic algorithm is applied to an initial population of possible solutions comprising the user's initial solution, together with the optimization criterion and solution limitations, to evolve it over a number of generations in a population of high-performance solutions relating to the optimization criterion, and the results indicate that after 50 generations. A layout, minimizing the traveling distance between the temporary facilities, is presented with the best solution to the population.

Mawdesley et al. (2002) utilized an increased genetic algorithm in order to model the cost of positioning and moving the short-lived facilities. The model makes the inter-facility distances possible and is based on the coordinate systems for facilities representation. The origin of the coordinate system of the site assumed as rectangular is one of its corners. The efficiencies of four crossovers and four mutation operators have been tested for determining the optimum layout for a problem proposed and solved. The performed tests showed that it is the best without a mutation. Moreover, this combination always detected the optimum in the specific problem being studied. The surprising thing is that it would be expected to sometimes converge to local optima instead of always finding the global optimum, without any mutation.

Elbeltagi et al. (2004) submitted a layout planning approach which considers both safety and productivity. Primarily, the safety issues on the construction sites are reviewed, in addition, the factors contributing to unsafe sites are also summarized. Then, a procedure which is in integration with a scheduling tool is developed for an optimum layout of the temporary facilities. The site layout planning had three aspects: (1) detecting the impermanent facilities and services needed on the site for health and safety reasons, (2) detecting appropriate safety zones around the construction space to reduce or avoid accidents, and (3) detecting proximity weights of the facilities based on safety considerations and in this direction optimizing the positioning of facilities on site. The genetic algorithm technique for the optimization procedure is used in the process of placing on site. The results of the two site layouts performed along project duration with the consultant, the contractor, project managers, and site engineers demonstrated that the TFs were regulated in the proper locations. The processing time to get an optimum or near-optimum site layout was detected as about 185 min on a Pentium 900Mhz personal computer.

El-Rayes et al. (2005) offered a multi-objective optimization model for planning airport construction site layouts which is capable of minimizing both construction-related hazards and site layout costs, simultaneously. The model is performed using a multi-objective genetic algorithm. Three main stages were used to develop the optimization model: (1) a model formulation stage that embodies all principle decision variables and optimization objectives, (2) quality quantification stage that formulates new functions to allow the evaluation of construction quality in this optimization problem, and (3) model implementation stage that performs a multi-objective GA for highway construction to provide a synchronical optimization of construction time, cost, and quality. An application example was analyzed for illustrating the use of the model, and for demonstrating its capabilities in considering quality in the optimization process and in developing optimal trade-offs among construction time, cost, and quality.

Sanad et al. (2008) offered an optimization model developed for solving the site layout planning problem which considers safety and environmental issues and the actual distance between facilities. In the developed model, genetic algorithms are utilized as an optimization bed. The case studies selected for the application of the developed model and automated system were carried out in “Tanta University Educational Hospital” located in Tanta City, Egypt. When the effect of the population size and number of generations on the convergence of the optimum solution is considered, It is observed that the developed system performed poorly with small population sizes as well as a big number of generations is used.

2.2. Site Layout Planning by Ant Colony Optimization (ACO)

Ning and Lam (2013) suggested a multi-objective optimization (MOO) model utilizing modified Pareto-based ant colony optimization (ACO) algorithm. Because the model could find a Pareto solution (trade-off layout), the requirement of reducing cost is fulfilled and the site safety level is improved simultaneously. Moreover, the residential building case was applied in order to validate the proposed MOO model. For solving site layout problem, the principle of grids-recognition strategy is used to find the locations for the facilities. After that, the searching scope is diminished step-by-step so as to determine the locations for all facilities by the sequence of the descending ranking order of facilities' proportions.

2.3. Site Layout Planning by Multiobjective Particle Swarm Optimization (MOPSO)

Xu and Li (2012) suggested a multi-objective decision making (MODM) model designed for dynamic construction site layout planning problems under unclear random environment. Besides, they presented a permutation-based MOPSO to solve the model. In order to illustrate the effectiveness of the proposed model and algorithm, the approach was implemented to the Longtan large-scale water conservancy and the hydropower construction project. The algorithm used was analyzed according to qualitative and quantitative aspects. (1) Quantitative aspect is to compare with the GA which is mainly applied in the construction site layout problems with the algorithm used in the study. (2) Many metrics of performance used so as to measure the distance of the resulting non-dominated set to the Pareto-optimal front, in other words, the distribution of solutions and the extent of the obtained non-dominated front. Finally, in order to prove that whether the model and algorithm proposed is feasible and efficient, they were applied to a practical case.

2.4. Comparative Studies

Zhang and Wang (2008) suggested a particle swarm optimization (PSO) - based methodology to find a solution for the construction site unequal area facility layout problem. A priority-based particle representation of the candidate solutions was suggested for the layout problem. It was inferred that the particle represented solution with regard to priorities should be transformed to the specific layout plan by consideration of non-overlapping and geometric constraints, and results were also checked against a GA method for dealing with the construction site unequal-area layout problem on the same example. The GA method is based on the modified GA operators suggested by Li and Love (1998). The computational experiments based on the illustrative example showed that the PSO-based method needs fewer iterations to get optimal solutions, and is more effective than the GA method implemented using the same fitness function and the modified GA operators improved by Li and Love (1998).

Adrian et al. (2014) proposed three metaheuristic algorithms, which are Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO), to solve the construction site layout problem arising from facilities positioned in locations, thus total for construction cost and interactive cost owing to facility layout constraints is minimized. The craziness concept, crossmutate, and scramble mutation techniques are performed to augment the variety of the solutions and to save the algorithms from being trapped in local optima. The Design of Experiment approach (DOE) is used to determine the optimal parameters for each algorithm. Two case studies for the facility layout problem originated from the literature were used to compare rigorously of the three algorithms with regard to effectiveness, efficiency, and consistency. ANOVA test was used to compare the performances, and obtained conclusions from the results are: (i) the three algorithms performed evenly well in terms of effectiveness to find the optimal solution, (ii) to find the optimum result, ACO is the fastest among the three algorithms in terms of efficiency, followed by GA and then PSO, (iii) in terms of consistency, all methods are shown to be equally consistent with solving this construction site layout problem.

2.5. Knowledge-Based Systems

Zouein and Tommelein (1999) introduced a hybrid incremental algorithm to solve the restricted dynamic layout problem. The aim of the numerical problem formulation is to minimize transportation and relocation costs of resources which are subject to 2D geometric restrictions. The system used a hybrid incremental approach account for relative locations between facilities by imposing two-dimensional geometric restrictions. The resulting sequence of layouts is suboptimal in point of the stated objective. This is nevertheless a favorable result when no closed-form mathematical solution exists for solving a problem.

Zouein et al. (2002) suggested an innovative approach so as to evaluate accessibility during pre-construction site layout planning. It can present a heuristic and easily understood visualization outcome which explicitly revealed the insecure parts of the site layout plan. The tests about different problems with a varying number of blocks, proximity requirements, and constraints on the relative positions of facilities were applied to control the algorithm. In the main cases where the total objects- to-site-area ratio was under or equal to 60%, results are shown that the algorithm turned back close to optimal solutions in an acceptable time (less than 2 min) after 250 generations.

2.6. Construction Safety Requirements

The Occupational Safety and Health Administration (OSHA) shows a total of 323 construction worker deaths involving 307 crane incidents were identified from 1992-2006, an average of 22 construction worker deaths per. Of the 307 fatal crane incidents, 216 (71%) involved mobile or truck cranes. Sixteen of the fatal incidents involved tower cranes (5%), 13 involved floating or barge cranes (4%), and 12 involved overhead cranes (4%). The remaining 66 reports were not sufficiently detailed to determine the type of crane. Of the total 323 crane-related deaths, 102 were caused by overhead power line electrocutions (32%), 68 deaths were associated with crane collapses (21%), and 59 deaths involved a construction worker being struck by a crane load (18%). of the total (5%) tower crane-related fatal incidents, Struck by crane loads (21%) were the first leading cause of death, The second leading cause of crane-related deaths were the load falls from the tower crane (8%). Crane collapses (nearly 4%), and Overhead power line electrocutions (nearly 4%) were the third leading cause of death.

2.8. Literature Summary

The literature review disclosed that genetic algorithms (GAs) and advanced through the nineties and many studies showed the capabilities of GAs in designing facility layouts, and these algorithms demonstrated themselves as a general, robust and powerful search mechanism. Moreover, the literature review also disclosed that multi-objective ant colony optimization algorithm, multi-objective particle swarm optimization and multi-objective genetic algorithms can be used to overcome the multi-objective optimization problem. The three algorithms demonstrated nearly equally good performance from the point of effectiveness to find the optimal solution.

3. MATERIAL AND METHOD

In the recent times, construction site layout optimization has become one of the main concerns in the field of construction management because a suitable design and optimization have a large impact on project time, cost, and safety. It is offered in this research that the development of an expanded site layout planning model which is competent minimizing the risk of crane operation accidents ensued from improving the safety level and decreasing the total distance of interaction on the site, simultaneously. The different algorithms such as neural network, artificial intelligence, and genetic algorithm, and ACO algorithm were used to solve various CSLP problems as seen in the literature reviews. In this study, we used Multi-Objective Particle Swarm Optimization (MOPSO) based on Pareto Dominance Approach to solve the model proposed, because this algorithm very rare were used to solve various CSLP problems as seen in the literature reviews.

To reach the targets, the research work is arranged in five main research tasks in this study as in following;

1. Formulation of the model to minimize the safety risks of temporary facilities based upon the crane operations.
2. Formulation of the model to minimize the distance between facilities on the site;
3. Presentation of the two types of constraints is imposed on the generated solutions to ensure the development of practical site layout plans;
4. Presentation of the algorithm applied to solve site layout plans;
5. Evaluation of the proposed model by using the grid search method.

3.1. Formulation of the Model to Minimize the Safety Risks of Temporary Facilities Based Upon the Crane Operations

In the present model, Equation 3.1. was used to calculate safety risk (SR) of a temporary facility.

Safety Risk (SR) = Risk Magnitude (RM) *Probability of an accident (P) (3.1)

where;

(1) Risk Magnitude (RM) is the estimated magnitude of the risk for the provisional facility owing to the position of the tower crane. (see the Section 3.1.1 below for detailed formulation between Equations 3.2 and 3.7)
(2) The probability of an accident (P): is influenced by the distance between the facility and the tower crane. (see the Section 3.1.2 below for detailed formulation between Equations 3.11 and 3.1.2)

3.1.1 Risk Magnitude (RM)

Risk magnitude (RM) is concerned with the distance between the temporary facility and the tower crane. There are three types of risk to consider while calculating RM, as in following:

1. RM_{Ai} : presents the fatality & injury risks related with possible strucks on the temporary facility i by tower crane loads (The values were obtained from the results of the survey applied to the experts.).
2. RM_{Bi} : presents the fatality & injury risks related with possible load falls on the temporary facility i from the tower crane (The values were obtained from the results of the survey applied to the experts.).
3. $RM_{Ci=}$ presents the fatality & injury risks related to crane collapses on the temporary facility i (The values were obtained from the results of the survey applied to the experts.).

$$RM_i = \sum_{i=1}^{n}\left((RM_{Ai} + RM_{Bi} + RM_{Ci}) * 100\right) \quad \text{if} \quad 0 < distance \leq J \quad (3.2)$$

$RM_i = \sum_{i=1}^{n} RM_{Ci}$ if $J < distance \leq J + H$ (3.3)

$RM_i = 1/33*100$ if $distance > J + H$ (3.4)

Where;

$$RM_{Ai}=\sum_{i=1}^{n} \sum_{j=1}^{m}(RS_{Tfij} * W_{Ej}) \quad (3.5)$$

$$RM_{Bi}=\sum_{i=1}^{n} \sum_{j=1}^{m}(RS_{Tfij} * W_{Ej}) \quad (3.6)$$

$$RM_{Ci}=\sum_{i=1}^{n} \sum_{j=1}^{m}(RS_{Tfij} * W_{Ej}) \quad (3.7)$$

Where;

RM_i : risk magnitude (RM) of the facility i due to its possition with respect to the tower crane.

i: temporary facility identity

n: number of temporary facilities.

m: number of experts.

distance : distance between facility i and tower crane;

J: length of the tower crane (see Figure 3.1);

H: height of the tower crane (see Figure 3.1);

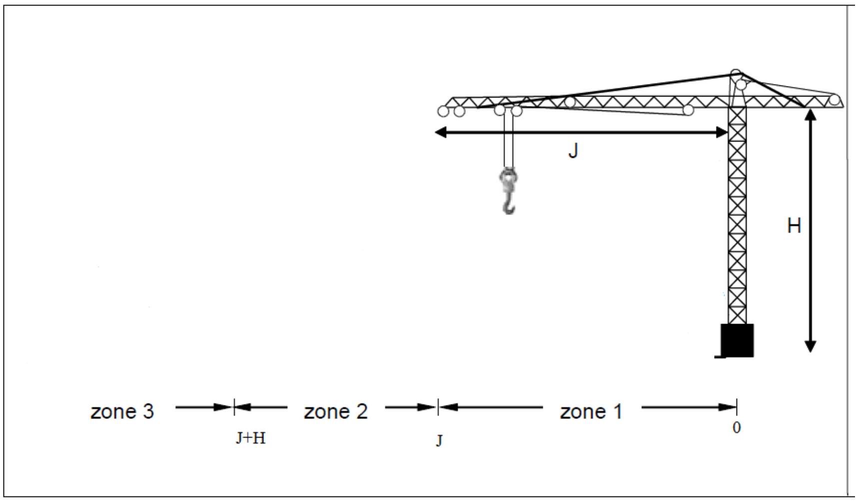


Figure 3.1. Tower Crane

$\boldsymbol{W_{Ej}}$:Introduces the weight of risk expert j (obtained from Zeng et al.2007) (Table3.1).

Table 3.1. W_{Ej} (Weight of risk expert j)

Expert	**Background**	$\boldsymbol{W_{Ej}}$**:**
E1	Project manager	0.25
E2	Construction manager	0.22
E3	Senior engineer	0.20
E4	Site engineer with 15 years experience	0.18
E5	Site engineer with 8 years experience	0.15
Total		0.25+0.22+0.20+0.18+0.15=1

(Zeng et al.2007)

$\boldsymbol{RS_{Tfij}}$**:** Illustrates the risk severity by the tower crane for temporary facilitiy i expressed by the expert j then changed into a constant depending Zeng et al.2007) (Table3.2).

Table 3.2. RS_{Tfi} (Risk severity)

Very low (VL)	Low (L)	Medium (M)	High (H)	Very high (VH)
0.2	0.4	0.6	0.8	1

(Zeng et al.2007)

3.1.2. Probability of an Accident (P)

The probability of an accident (p) is affected by the distance between the facility and the tower crane. $p(distance)$ is the function that determines the magnitude of the probability of an accident (p) and explained as follows.

The function of $p(distance)$ is affected by the distance between the facility and the tower crane and the space around the crane is divided into three zones (Khalafallah, 2006), as shown in Figure 3.2.

Zone 1: the area that covers the crane operating angles (0 < distance ≤ J); represents the highest sensitivity due to its vulnerability to struck loads and/or falling objects and/or collapse of the crane from the crane during its operations.

Zone 2: located between zones 1 and 3 (J < distance ≤J+H); represents an intermediate level of sensitivity due to its medium vulnerability to crane accidents such as the collapse of the crane.

Zone 3: the area that is outside the crane risk areas (J+H < distance ≤ J+ (3*H)/2); represents a low level of sensitivity due to its minor vulnerability to be thrown objects during the crane collapse.

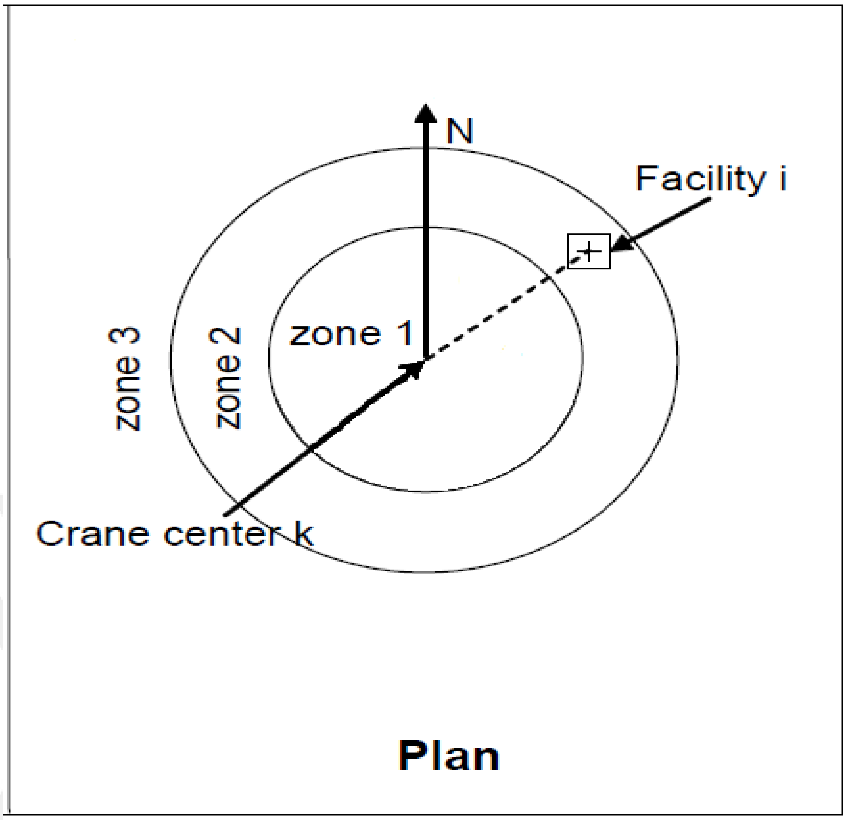


Figure 3.2 Zones Around Tower Crane

P_i(distance):

$$0 < distance \leq J \quad \Rightarrow \quad Pi(distance) = 29/33 \qquad (3.8)$$

$$J < distance \leq J + \frac{H}{2} \quad \Rightarrow \quad Pi(distance) = \frac{52 * (J - distance)}{33 * H} + \frac{29}{33} \qquad (3.8)$$

$$J + H/2 < distance \leq J + H \quad \Rightarrow \quad Pi(distance) = \frac{4 * (J - distance)}{33 * H} + \frac{5}{33} \qquad (3.10)$$

$$J + H < distance \leq J + \frac{3 * H}{2} \quad \Rightarrow \quad Pi(distance) = \frac{2 * (J - distance)}{33 * H} + \frac{1}{11} \qquad (3.11)$$

distance= distance between facility i and tower crane;

J=length of the tower crane;

H= height of the tower crane

The problem of risk minimization is then expressed as in Equation 3.12.

$$Minimize\ Safety\ Risk(SR) = \sum_{i=1}^{n} RM_i * Pi(distance) \quad (3.12)$$

3.2. Formulation of the Model to Minimize the Distance Between Facilities on the Site

The second optimization target of the present model is to reduce the traveling cost of resources to a minimum because of the distance between the facilities of the sites. This may be obtained when the proximity weights are used as depending on the desired closeness between the facilities.

Table 3.3 shows one common scale used for the current problem which was also used in industrial facility layout planning (Hegazy and Elbeltagi 1999) and the convenient scales were chosen by the experts.

Table 3.3. The six-value scale commonly used in industrial facility layout planning (Hegazy and Elbeltagi 1999).

Desired closeness between facilities	Proximity weights for various facilities relationships (W_{ij})
Absolutely necessary (A)	6^5=7776
Especially important (E)	6^4=1296
Important (I)	6^3=216
Ordinary closeness(O)	6^2=36
Unimportant (U)	6^1=6
Undesirable (X)	0

The traditional measure used to calculate a specific layout is a weighted sum of all travel distances as follows (Sanad et al., 2008):

$$Minimize: \sum_{i=1}^{p-1} \sum_{j=i+1}^{p} w_{ij} d_{ij} \tag{3.13}$$

$$d_{ij} = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2} \tag{3.14}$$

Where

w_{ij}= Proximity weights representing the actual transportation cost per unit distance between facilities i and j (Table 3.6.)
d_{ij}= distance between facilities i and j; (the values are attained from plans)
X_i, Y_i= coordinates of the center of gravity of facility I; (the values are attained from the plans)
X_j, Y_j= coordinates of the center of gravity of facility j; (the values are attained from the plans)
p= total number of facilities on site;

3.3. Optimization Constraints

In the present model, two types of constraints are imposed on the generated solutions to assure the improvement of practical site layout plans: (1) boundary constraints; and (2) overlap constraints. Boundary constraints are required to ensure that temporary facilities are located within the site boundaries, on the other hand, avoiding the overlap of facilities on site is essential for overlap constraints.

3.3.1. Boundary Constraints

In this model, boundary constraints are investigated for each solution using the following four-step algorithm so as to provide that each facility is located within the boundaries of the site:

For each temporary facility i the gap between facilities and boundary in the X,Y direction are determined according to the coordinates of its center of gravity (Xi, Yi), and its length in the X direction (Lxi) and width in the Y direction (Wyi) .

In X direction boundary constraints are satisfied if:

$$Xi + Lxi/2 + \delta \leq UX; \text{ and} \tag{3.15}$$

$$Xi - Lxi/2 - \delta \geq LX. \tag{3.16}$$

where (see Figure 3.4);

δ : gap between facilities and boundary in the X,Y direction.

UX : the right boundary of the site space.

LX : the left boundary of the site space.

In Y direction boundary constraints are satisfied if:

$$Yi + Wyi/2 + \delta \leq UY; \text{ and} \tag{3.17}$$

$$Yi - Wyi/2 - \delta \geq LY. \tag{3.18}$$

where (see Figure 3.4);

UY : the upper boundary of the site space.

LY : the lower boundary of the site space.

When all the positions in X and Y directions are satisfied, then the facility i is compatible with boundary constraints. In the contrary case, this type of constraint is violated, so it should be dismissed (Khalafallah, 2006).

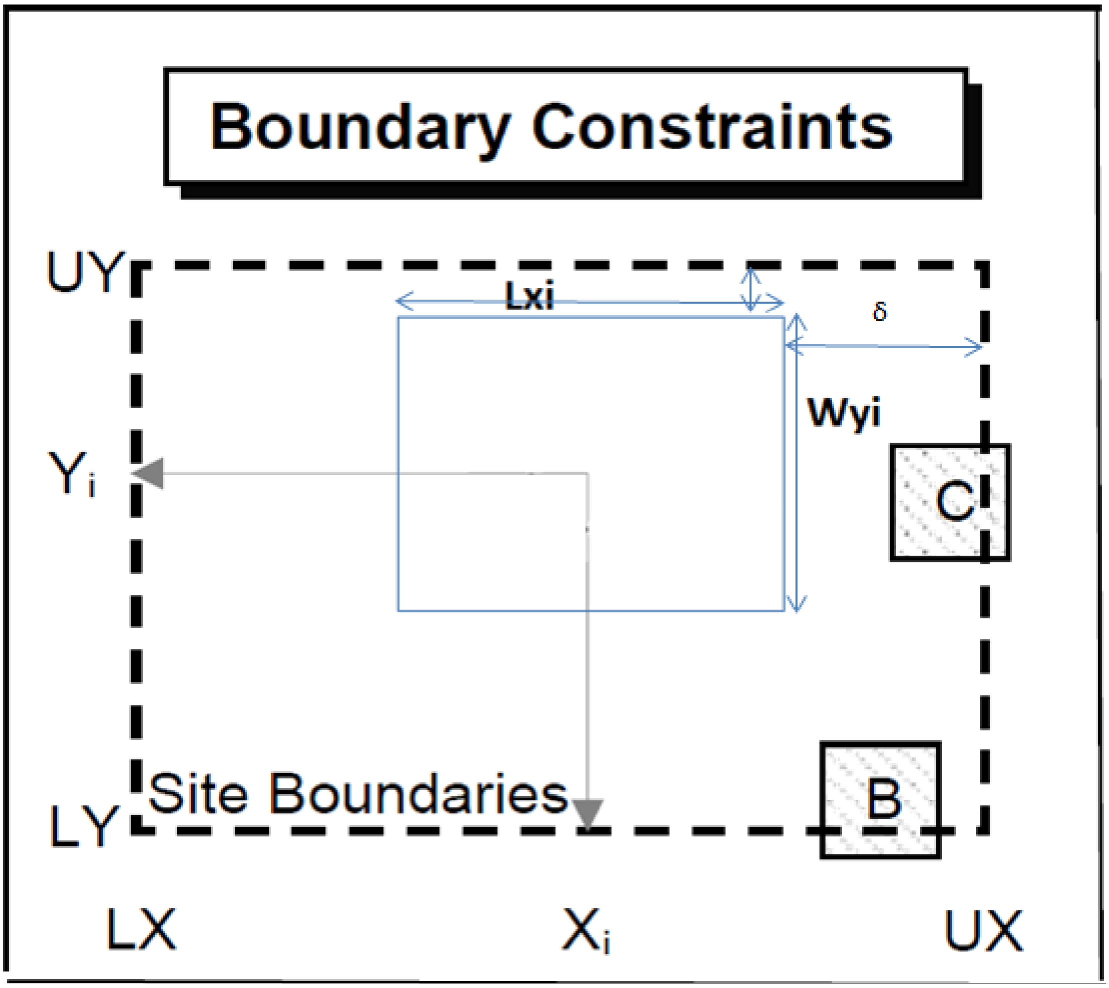


Figure 3.3 Boundary Constraints

3.3.2. Overlap Constraints

In order to ensure that no overlap occurs between facilities on site, overlap constraints are examined using the following steps (see Figure 3.3 and Figure 3.4.)

In X direction Overlap Constraints between facilities i and j are satisfied if:

$$(|Xi - Xj| \geq (Lxi/2 + Lxj/2+\delta)) \tag{3.19}$$

In Y direction Overlap Constraints between facilities i and j are satisfied if:

$$(|Yi - Yj| \geq (Lyi/2 + Lyj/2)/2+\delta)) \tag{3.20}$$

If overlaps are encountered in X or Y directions, then there is an overlap between the two facilities as shown in Figure 3.4. and therefore this solution should be precluded. Otherwise, overlap constraints are satisfied.

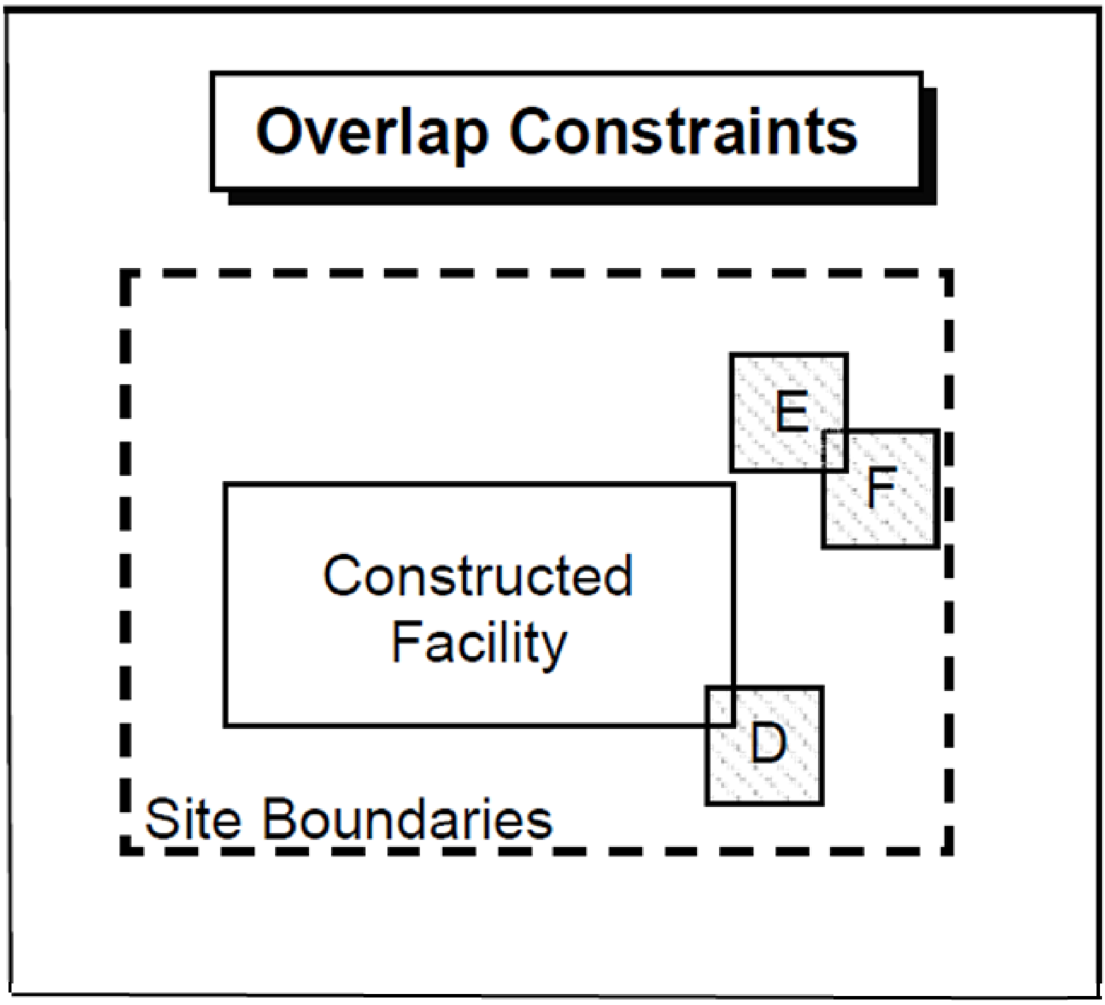


Figure 3.4 Overlap Constraints

3.4. The Algorithm

It has seen in the literature reviews that varied algorithms such as neural networks, artificial intelligence, and genetic algorithm and ACO algorithm were operated to resolve a variety of construction site layout problems (CSLP).

In this study, Multi-Objective Particle Swarm Optimization (MOPSO) based on Pareto Dominance Approach will be applied to solve the model proposed.

The definitions used for the proposed Multi-Objective Optimization search algorithm are explained as the following:

3.4.1. Multi-Objective Optimization

The best part of the real-world engineering optimization problems are multi-objective in nature because they ordinarily have diverse (probably conflicting) objectives that must also be satisfied (Baghel 2009) . The multi-objective optimization problems are composed of various objectives that are required to be handled at the same time. Such problems emerge in many applications in which two or more, sometimes competing and/or incomparable objective functions need to be minimized, simultaneously. In this case, multi-objective optimization can be described (that is to say) as the problem of finding: “A vector of decision variables which fulfills constraints and optimizes a vector function of which elements indicate the objective functions. These functions are from a mathematical definition of performance criteria that generally conflict with each other. Therefore the expression " optimize" signifies finding such a solution that gives the values of all the objective functions admissible to the decision maker.’’ (Baghel 2009)

3.4.2. Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) is a brilliant optimization algorithm depended on the Swarm Intelligence. A simple mathematical model developed by Kennedy and Eberhart in 1995 (Chaudhary and Dua, 2012) which describes the social behavior of birds and fish underlies that algorithm.

The model is generally based on the main principles of the self-organization that is utilized to define the dynamics of complex systems. Some systems having swarm intelligence ability are definitely unreachable for any of system units, therefore they achieve a higher level of intelligence. For instance, when a flock of birds is considered as a society that has such complex behavior patterns, it is seen that they behave as one that is beyond their intelligence level of any of birds in the flock and undoubtedly that cannot be separated into independent subparts. However, any members of the flock can create these complex patterns by the way of simple and recurring tasks. A very simplified model of the social behavior is used by PSO in order to solve the optimization problems in a cooperative and smart framework. PSO is successfully utilized for various optimization problems due to being one of the most advantageous and prominent metaheuristics.

The basic steps of PSO algorithm for the single-objective case are, in following:

1. Initialize the swarm
2. For each particle in the swarm:
    A. Select leader
    B. Update velocity
    C. Update position
3. Repeat

3.4.3. Multi objective Particle Swarm Optimization (MOPSO)

The Multi-Objective Particle Swarm Optimization or MOPSO algorithm is provided from the PESA2 algorithm and the operators of the PSO method are utilized rather than the genetic operators. In 2004, Coello presented this algorithm in comparison with NSGA II (Coello and Lechuga, 2014). It presents a multi-objective version of PSO because of embodying the Pareto Envelope and grid making technique, like similar to Pareto Envelope-based Selection Algorithm to overcome the multi-objective optimization problems. The particles in MOPSO work exactly like PSO, i.e. they share information and move towards global best particles and their own personal (local) best memory. Nevertheless, on the contrary of PSO, there are several criteria more than one to detect and describe in the best way. The repository is a sub-swarm where all of the non-dominated particles in the swarm are gathered, and each particle selects its global best target, among members of this Repository. Domination based and stochastic rules are used for the personal (local) best particle.

While selecting the best particle and the best personal recollection during the process of the algorithm, as in the classical PSO one objective relating to the issue, the answer is clearly the multi-objective problems. Neither space is feasible arranged nor is described. Therefore, a change should occur in the algorithm. The changes in MOPSO concept (Repository) are added. This signifies that a separate archive answer is found outside of the algorithm which is stored in the archive. The Pareto Front is members of the approximate archive. Thereby each particle of the multi-objective algorithm is in the third. This motion that imitates the collective memory of the particles (Global Best) is, of their leader haphazardly chosen from the archive stems. Another dissimilarity of the multi-objective version of MOPSO in detecting the best personal recollection (Personal Best) should be the new location of each particle to compare the best personal recollection. If the new position is a more appropriate point, this point will turn into the best personal recollection of the particles. The present model is performed as a multi-objective particle swarm optimization and this algorithm is solved with MATLAB so as to permit the generation of near optimal site layout plans that maximizes construction safety, on the other hand, minimizes spacing of resources, meantime satisfying all the useful layout constraints explained earlier. Computational steps were carried out according to Coello and Lechuga (2012).

3.4.4. Pareto front

It is not likely to notify an exact point as the answer, in solving the multi-objective problems. Because if we find a point where one of the target functions is minimal, there will be another target function which is not minimal at this point. The optimization problem is not a point, but a curve where every point is optimized with regard to just one of the objective functions. Besides, these points will never be dominated by each other (Hosseini et al., 2014).

3.4.5. Domination

In multi objective optimization the concept of domination is used for comparing the points. If all the X1 solution are not worse than all solution X2 in all objectives, or if all the X1 solutions are equal to X2 but only in one case or one dimension X1 is better than X2, then it can be said that X1 will dominate X2. The mathematical expression of the domination concept is as follows (Hosseini et al., 2014):

x1 dominate x2 if:

$f(x_1) \geq f(x_2)$

$f(x_1) < f(x_2)$

3.5. Grid Search Method

If the necessary maximum is known to be within a definite area described by upper and lower bounds of each of the independent variables, at that case the grid search method can be applied (Ataei and Osanloo, 2004). All of the probable states would be systematically searched by this method. To this end, one must establish a grid over the area of the interest and appraise the objective function at each node of the grid. Thereafter the computation of the objective function values in all the nodes of the grid, it might be interpolated and be found maximum between the gridlines.

Although this method is very effortless to program, nevertheless it is very unproductive. Because excessive computational time is needed. On the other hand, the method can be utilized to find a good starting space for one of the most effective methods. The grid search method was used in this study to determine the starting space for the multi-objective particle swarm optimization (MOPSO) method(Figure 3.5).

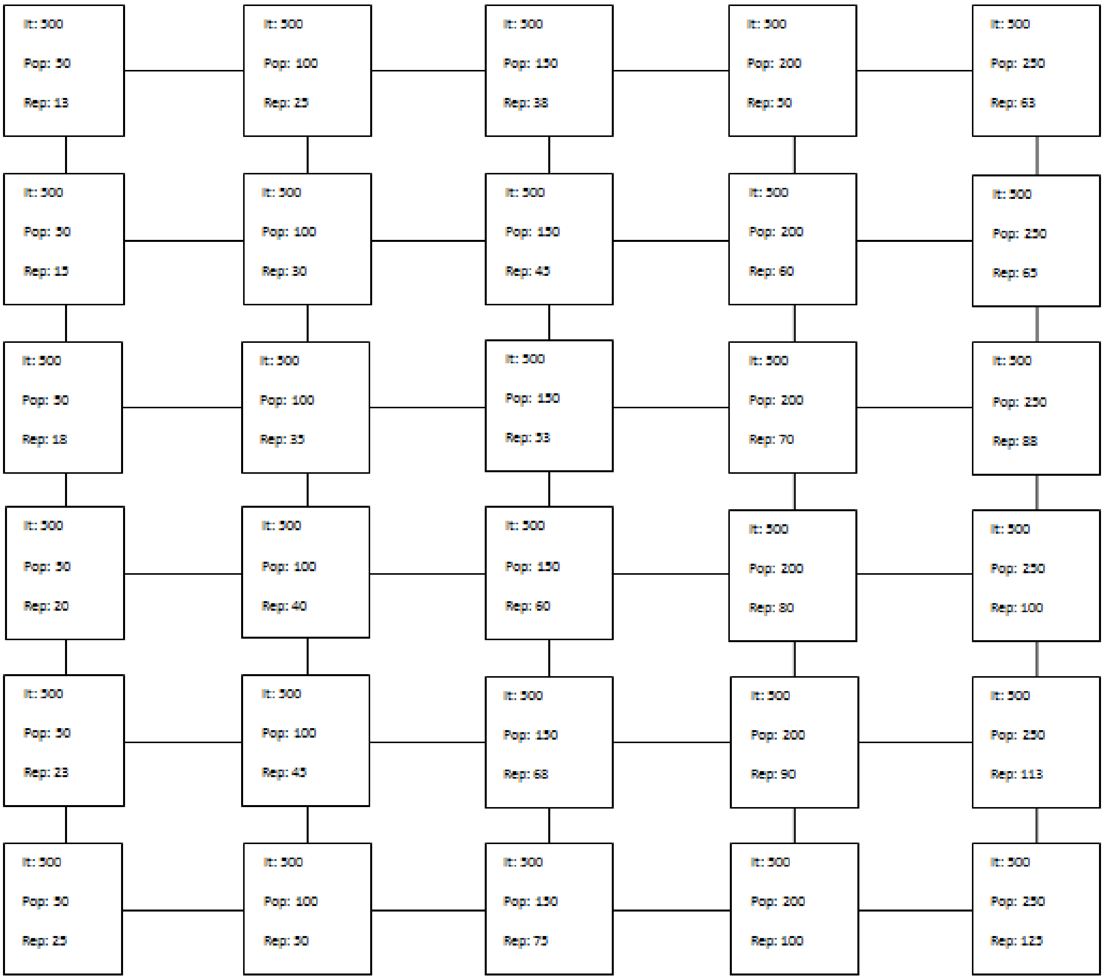


Figure 3.5. Grid Search

where;

1. Iteration (it): A more responsive way to progress is to go several times through the various development fields, constructing a better comprehension of the necessities, augmenting the development organization, and finally delivering a range of implementations that are progressively more complete. This is denominated as an iterative lifecycle. Each transition through the sequence of process fields is named an iteration.
2. Population size (pop): is a crucial parameter influencing the performance of an Evolutionary Computation model. The population size depends on the character of the problem, on the other hand, characteristically includes

several hundreds or thousands of possible solutions. A changeable population size scheme is taken into consideration to potentially advantageous to enhance the quality of the solutions and to speed up fitness progression.

3. Repository (rep): Repository members are non- dominant members of the problem which as storage collects the best points, obtained in the course of the stages of performing optimization algorithm. There are two conditions selecting these members:

    a) Not being managed by the repository members
    b) The most distributions of the repository members

4. RESEARCH AND DISCUSSION

The principal research results of this study were examined and divided into three main sections, as in following:

1. Multi-objective site layout optimization system
2. Application example
3. Model evaluation and results verification

4.1. Multi-Objective Site Layout Optimization System

This section presents the structure of the developed model for Multi-objective site layout optimization. This section analyzes the structure of a developmental model for Multi-objective site layout optimization. The principal purpose of the present system is to provide convenient automated support for the construction planners who need to optimize the design of site layout plans. The system is implemented and integrated into three main modules: (1) A comprehensive multi-objective optimization module that optimizes and integrates entire effects of site layout planning with minimizing the risk of Crane Operations accidents occurred to enhance the safety level and to minimize the total distance of interaction; (2) a relational database module to promote the storage and retrieval of construction site layout data and the produced optimization results; (3) a user interface module in order to facilitate the input of project data and the analysis of the produced optimal site layout plans (Figure 4.1). These three modules are explained in more detail in the following section Figure 4.1.

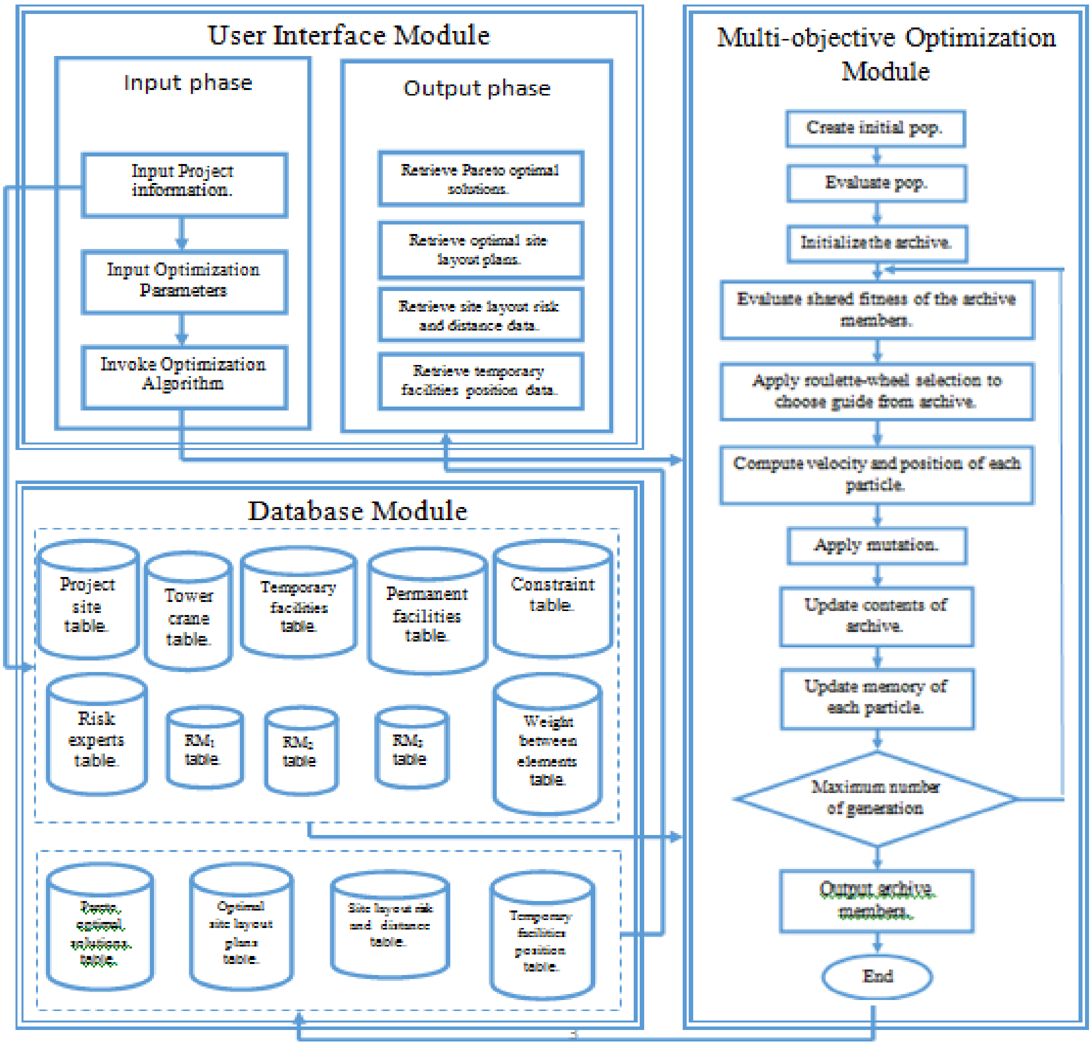


Figure 4.1. Multi-Objective Optimization Module

4.1.1. Multi-Objective Optimization Module

Integrating seamlessly the two site layout optimization models which were previously explained in Chapter 3 is the major function of the comprehensive multi-objective optimization module. Correspondingly, the optimization objectives in this entire model comprise: (1) to minimize the risk of crane operations accidents taken place to improve the safety level, (2) to reduce the total distance of interaction. So as to search and identify optimal coordinates for the gravity center of each temporary facility on site, this overall optimization model is developed. As shown in Figure 4.1. the overall model initiates the optimization operations by producing a set of random nominee site layout solutions. By using this set of candidate solutions, new solutions are regenerated through a number of multi-objective particle swarm optimization operations and this process that inclines to eliminate the worst candidate site layout solutions and maintain the best ones. While selecting the best candidates, each candidate site layout solution is appraised according to a number of criteria, containing: (1) the safety of overall construction; (2) the total distance of interactions. The set of aforementioned operations is reiterated over a number of cycles, producing better and better solutions until the solutions improve a stable state.

4.1.2. Database Module

The major function of this module is to develop a relational database to store the required site layout input data (e.g. temporary facilities information, permanent facilities information, tower crane data) and the generated optimal site layout data. This module is constituted of fourteen main tables that are designed to store the following site layout planning data: (1) project site data; (2) tower crane data; (3) temporary facilities information; (4) permanent facilities information; (5) constraint data; (6) risk experts attribute; (7) RM_{Ai} data (the fatality & injury risks related with possible strucks on the temporary facility i by tower crane loads); (8) RM_{Bi} data (the fatality & injury risks related to possible load falls on the temporary facility i from the tower crane); (9) RM_{Ci} data(the fatality & injury risks related with crane collapses on the temporary facility i) ; (10) weight between elements; (11) site layout risk and distance data ; (12) temporary facilities position data; (13) optimal locations of temporary facilities; and (14) optimal tradeoff solutions.

4.1.3. User Interface Module

The user interface module is developed in order to facilitate the input of all necessary site layout planning data and the output of producing optimal site layout designs. This module is designed to perform its functions in two main phases: (1) an input phase to store (e.g. construction site data, temporary and permanent facilities information, risk experts attributes and multi-objective particle swarm optimization parameters); and (2) an output phase to simplify the retrieval of the optimal site layout plans. The module is implemented using MATLAB GUI (Graphical User Interfaces in MATLAB) to utilize from its advanced competencies in facilitating the development of graphical user-friendly interfaces and the integration of all the developed modules. Figure 4.1. illustrates the relationships and interactions between the input and output phases in the present module and the other modules of the system. A detailed discussion of the data flow during the input and output phases were provided by the following two sections:

4.1.3.1. Input Phase

The input phase is intended to assist construction planners in order to enter and store all the required planning and optimization data for optimizing the site layout plan through Input module or relevant Excel file. In the course of this phase, it is asked from the user to enter a site layout planning data in (1) project site data, (2) tower crane data and (3) Constraint data as shown in Figure 4.2.

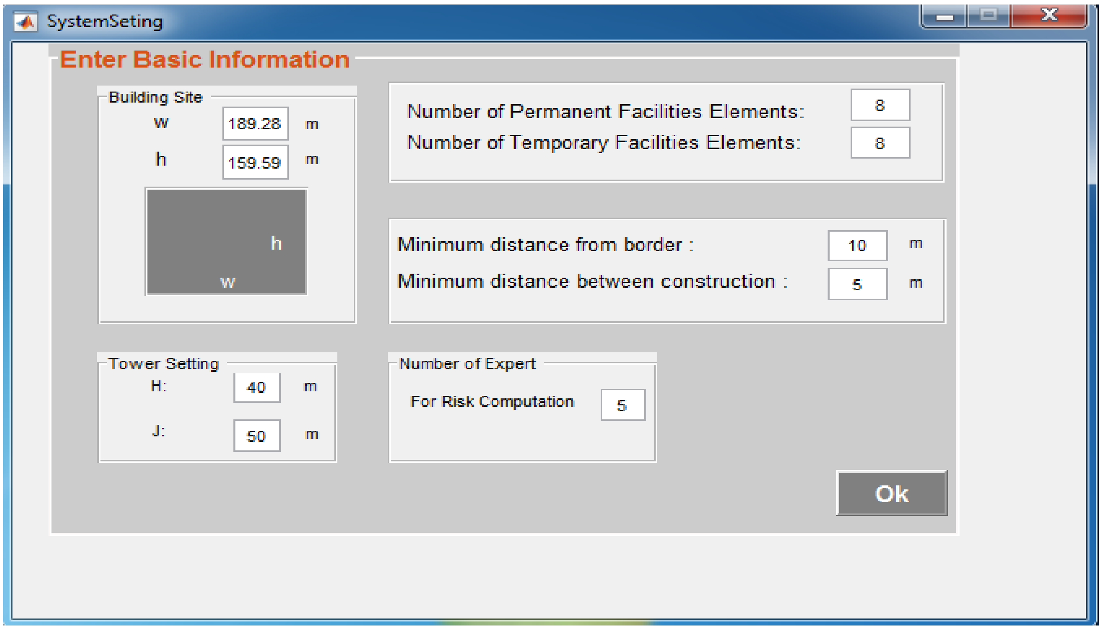


Figure 4.2 Input module (project site data, tower crane data and Constraint data)

4. Information about temporary facilities. As shown in Figure 4.3 and Figure 4.4.

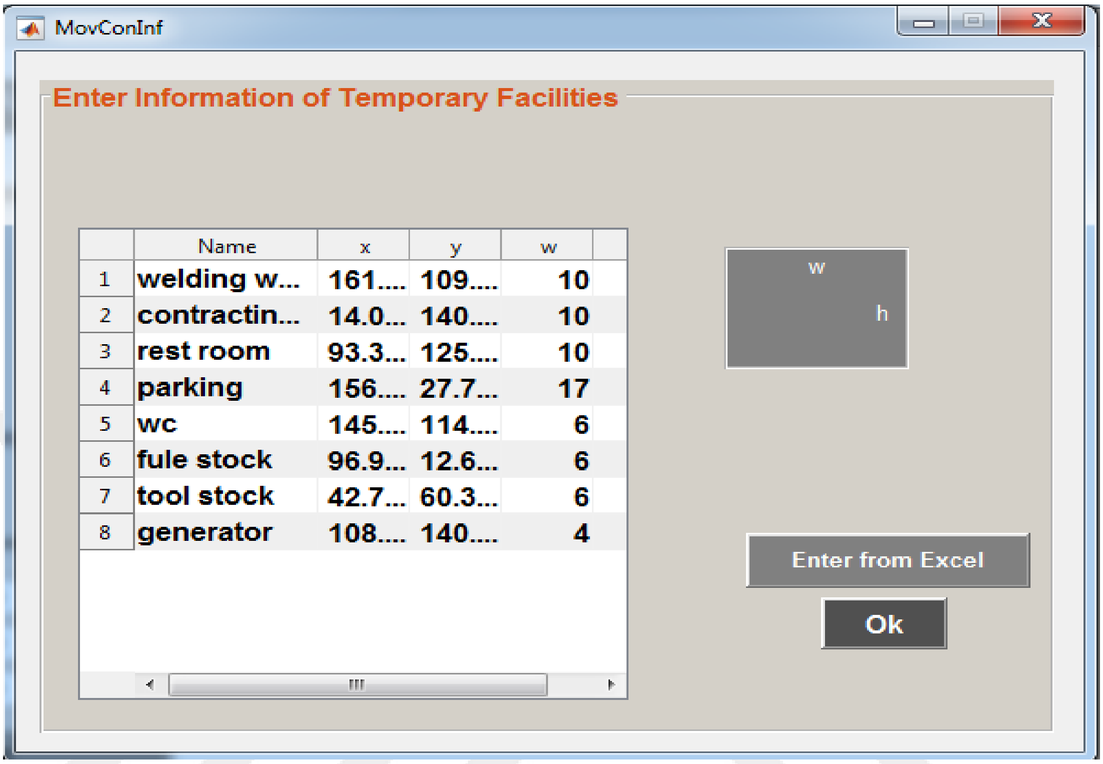


Figure 4.3 Input temporary facilities information through input module

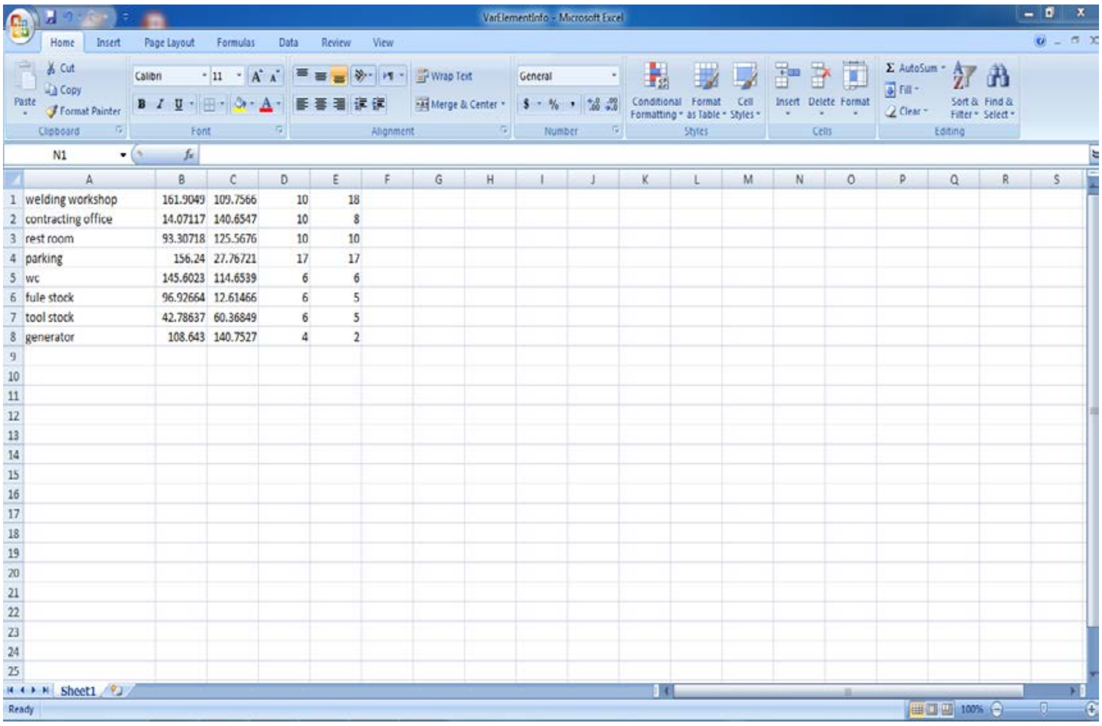


Figure 4.4 Input temporary facilities information through Excel file

5. Information about permanent facilities as shown in Figure 4.5 and Figure 4.6.

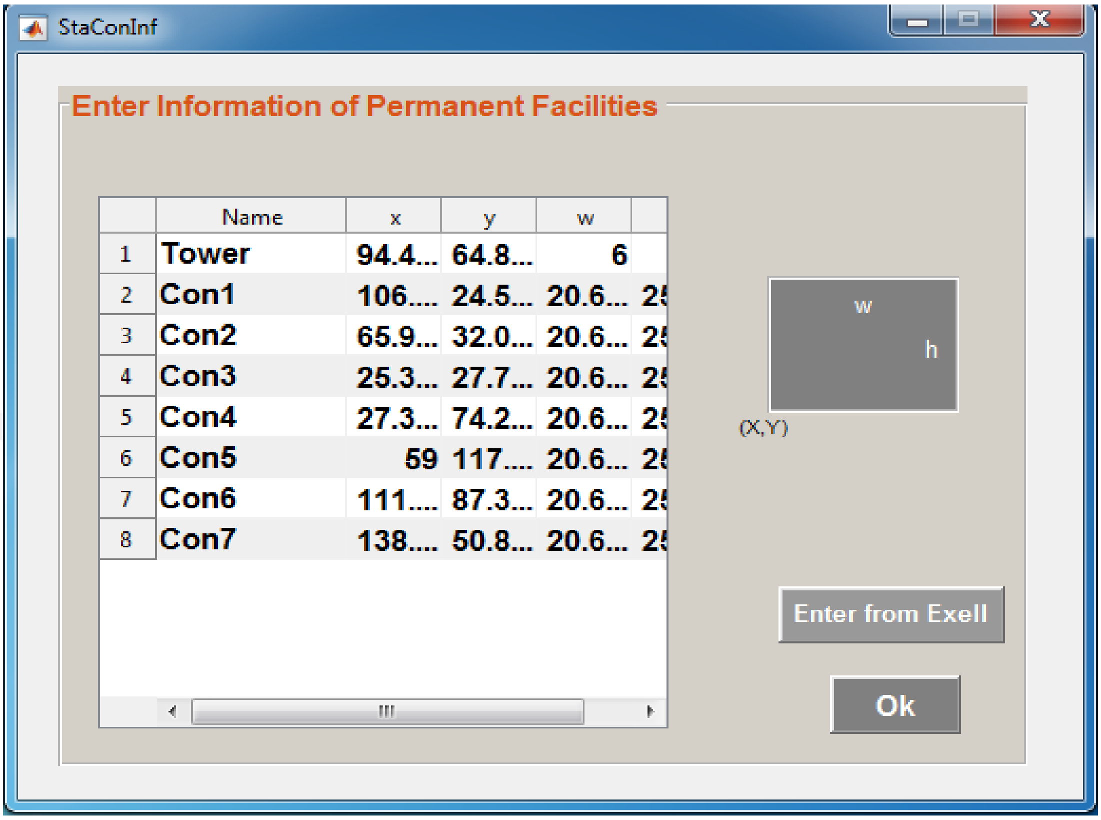


Figure 4.5 Input Permanent facilities information through input module

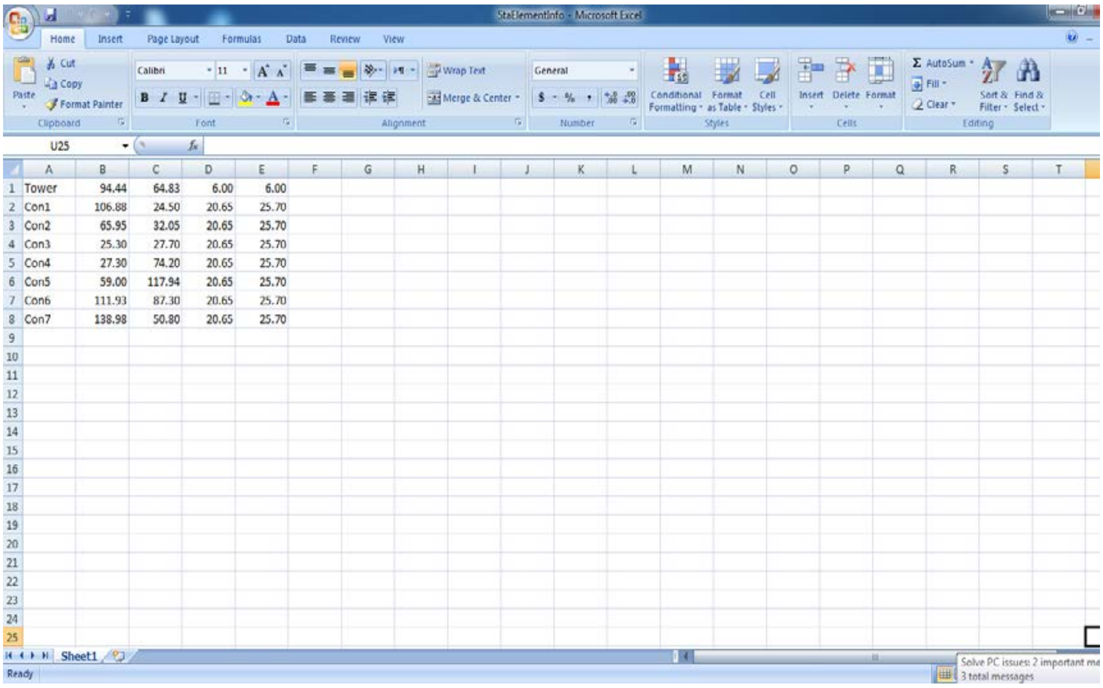


Figure 4.6 Input Permanent facilities information through Excel file

6. risk experts attributes as shown in Figure 4.7 and Figure 4.8

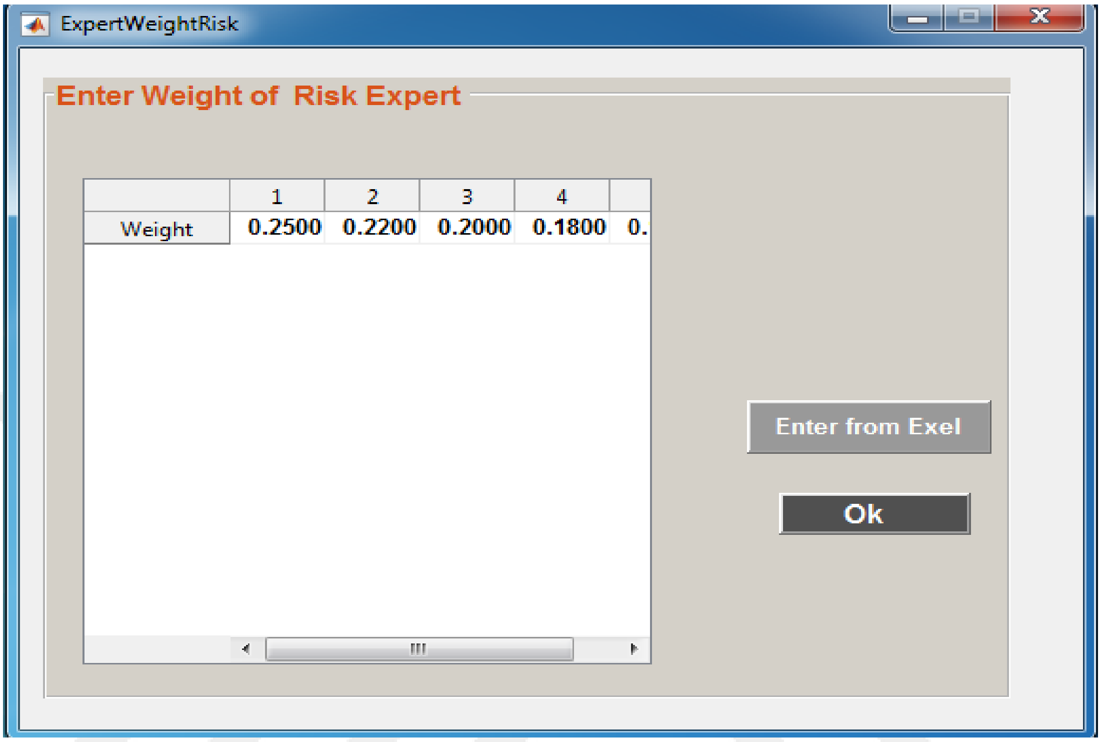


Figure 4.7 Input Risk Experts Attributes Through Input Module

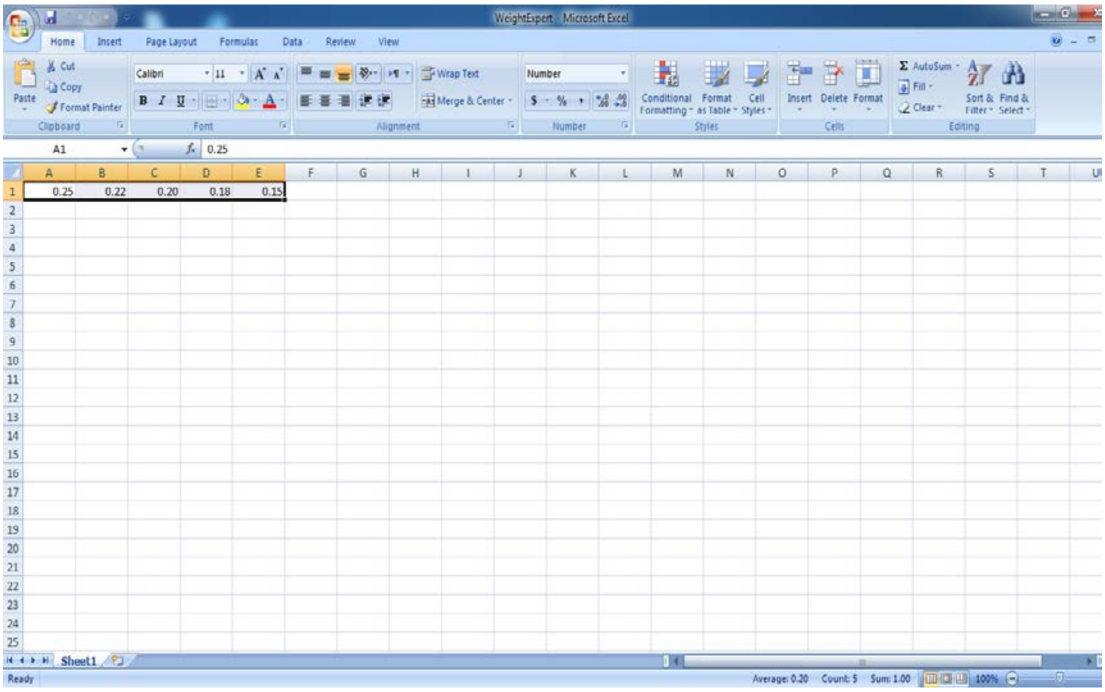


Figure 4.8 Input Risk Experts Attributes Through Excel File

7. RM_{Ai} data as shown in Figure 4.9 and Figure 4.10.

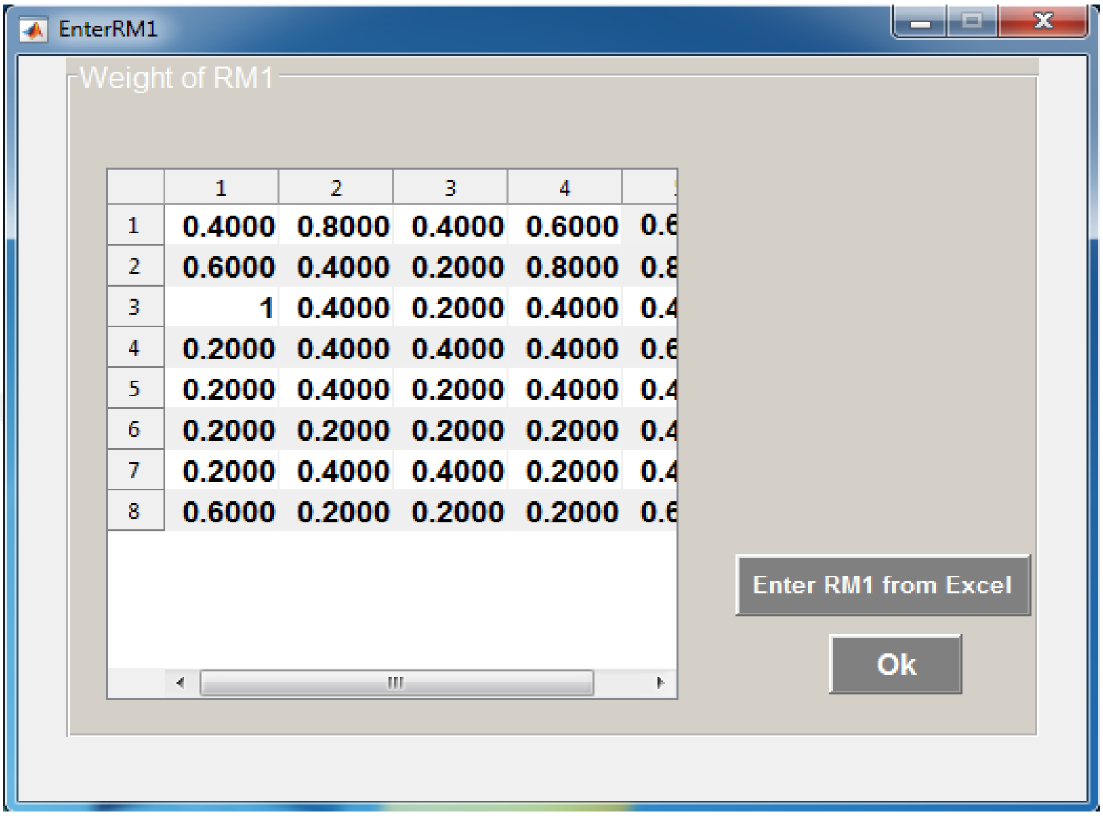


Figure 4.9 Input RM_{Ai} Data through Input Module

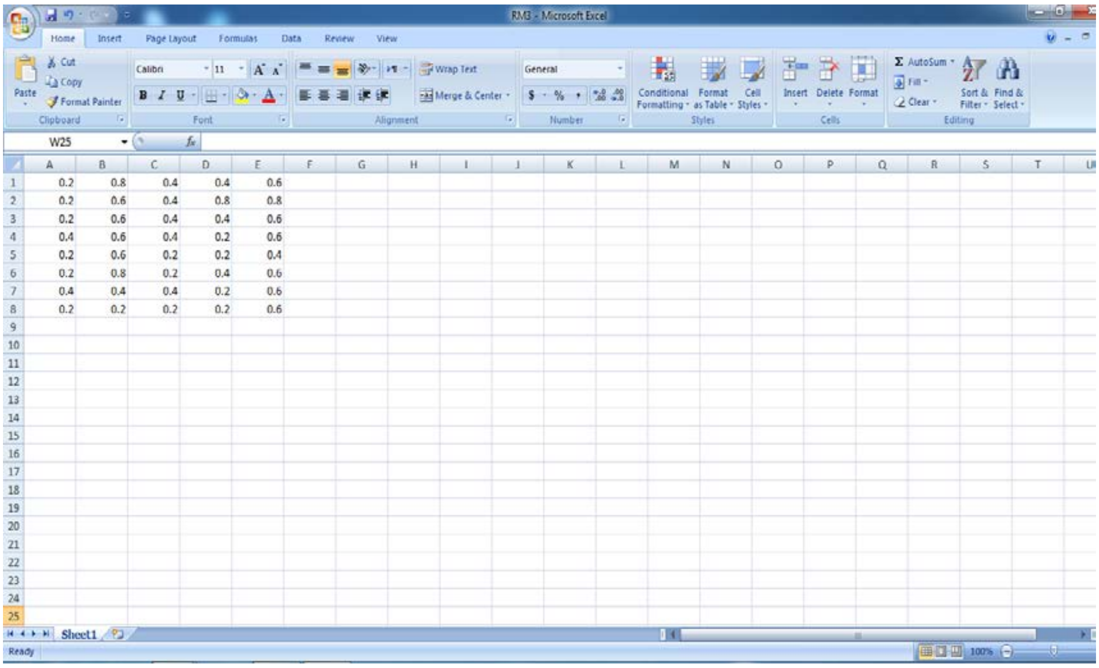


Figure 4.10 Input RM_{Ai} Data through Excel File

8. RM_{Bi} data as shown in Figure 4.11 and 4.12;

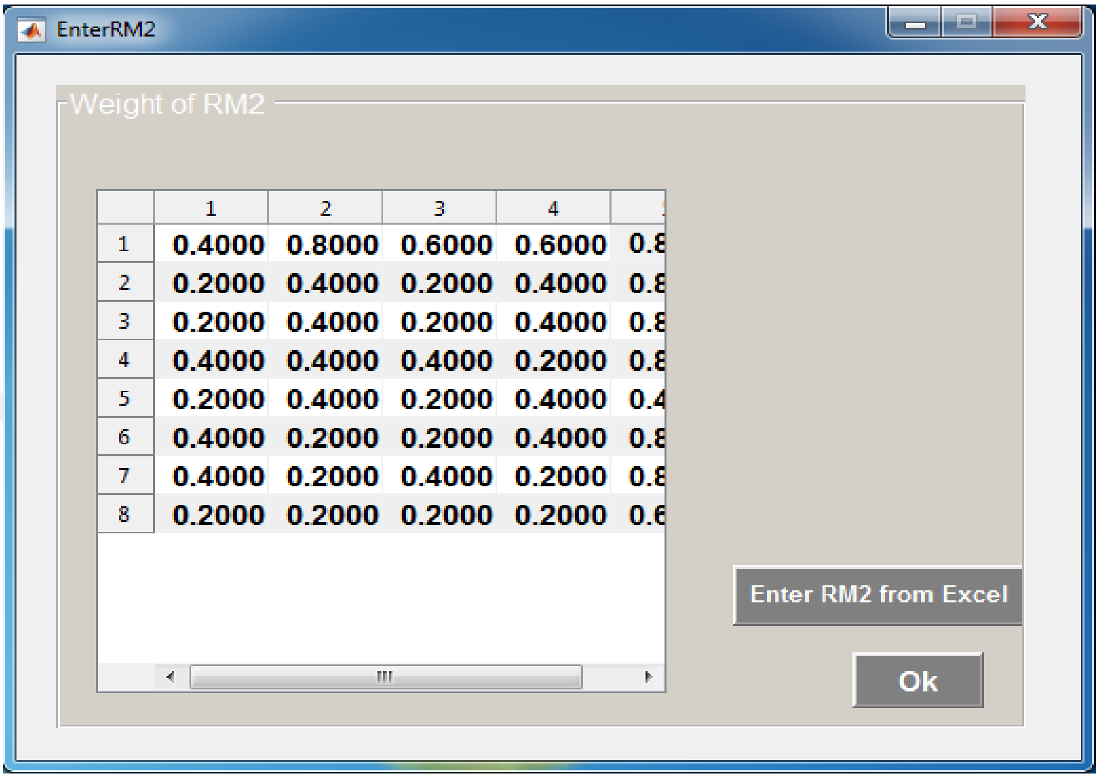


Figure 4.11 Input RM_{Bi} Data through Input Module

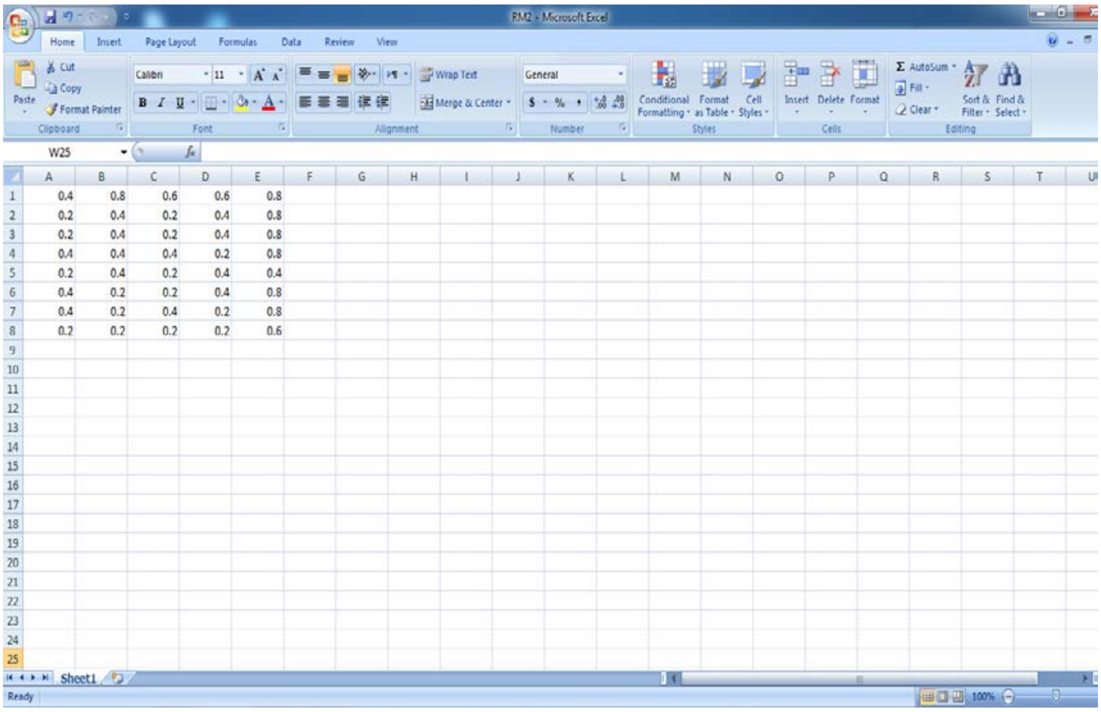


Figure 4.12 Input RM_{Bi} data through Excel File

9. RM_{Ci} data as shown in Figure 4.13 and 4.14.

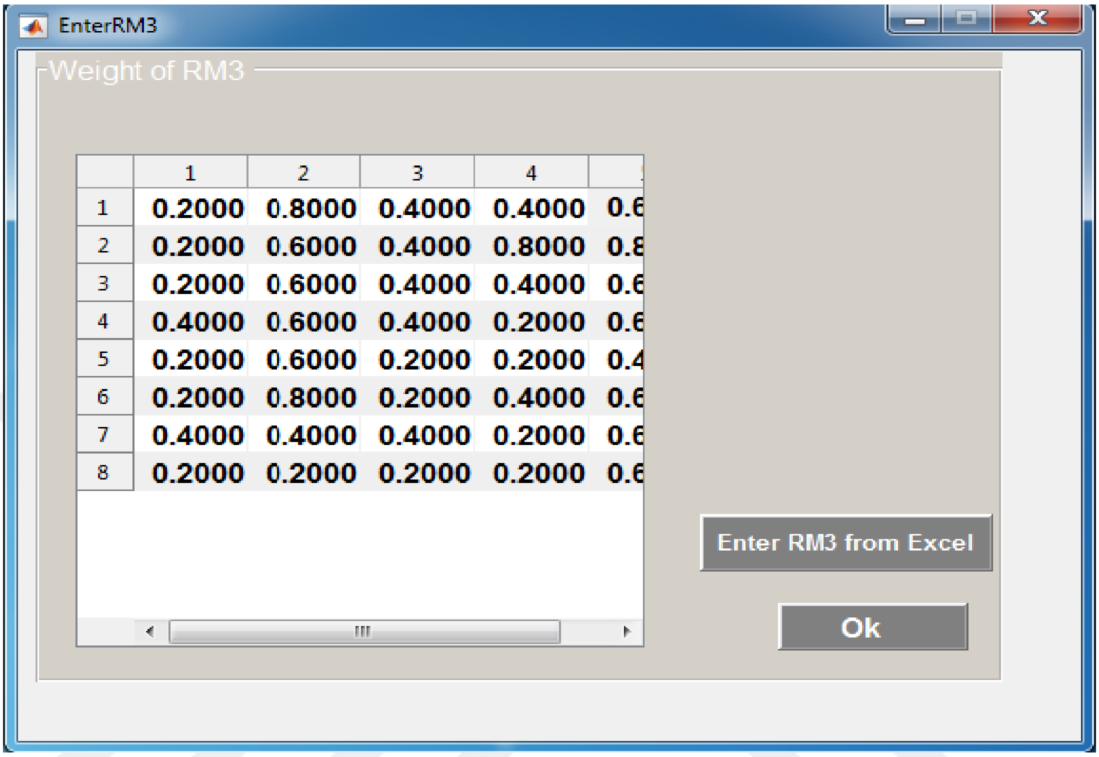


Figure 4.13 Input RM_{Ci} Data through Input Module

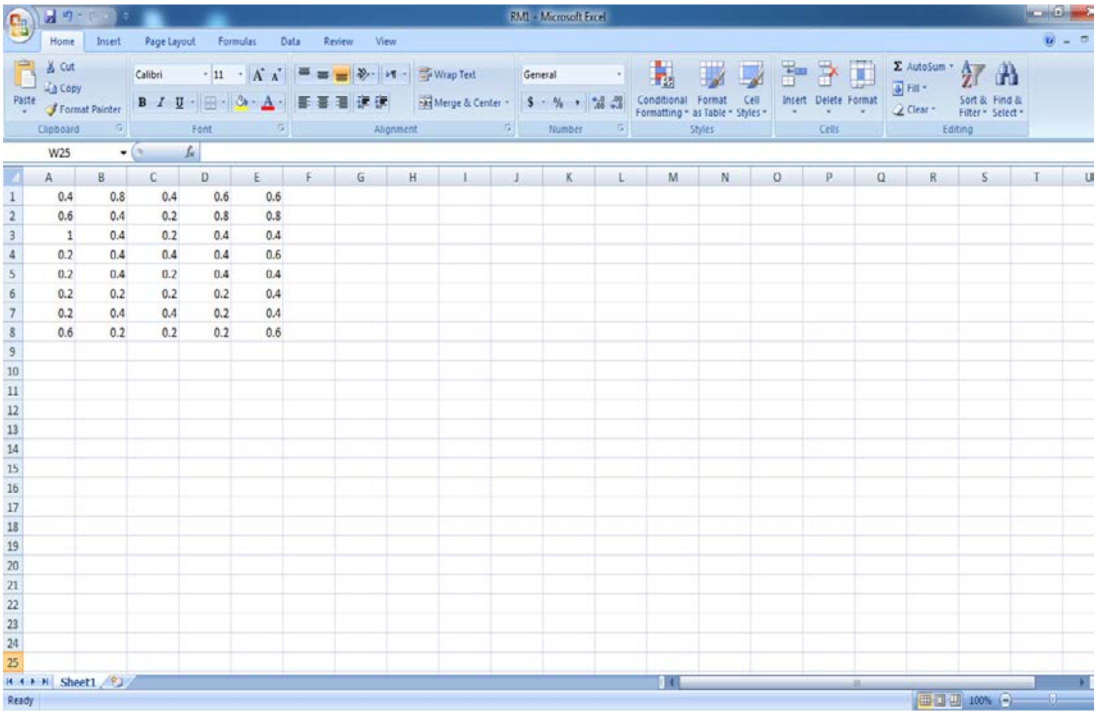
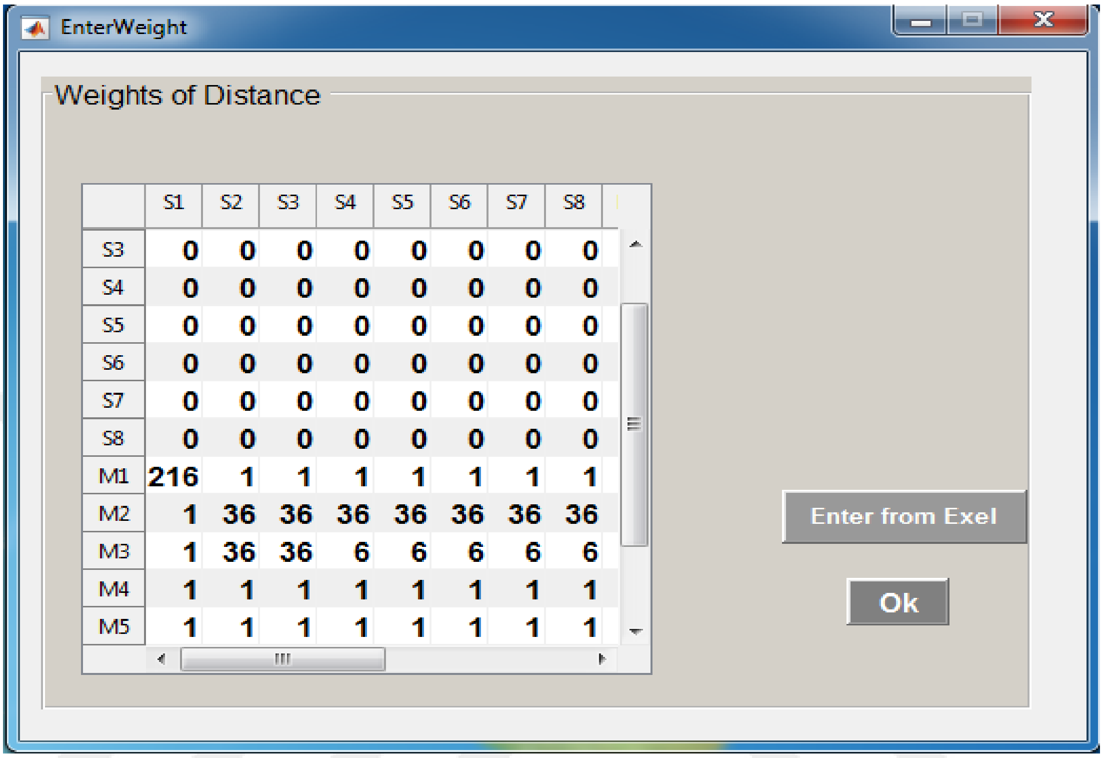


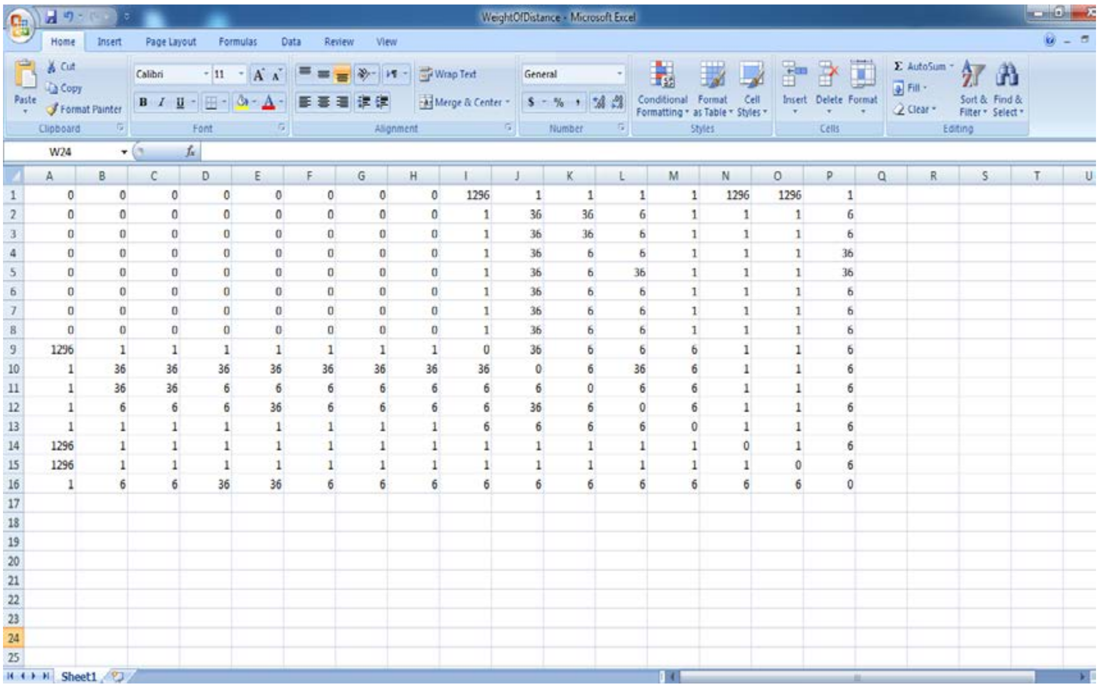
Figure 4.14 Input RM_{Ci} Data through Excel File

10. Weight between elements as shown in Figure 4.15 and 4.16.



	S1	S2	S3	S4	S5	S6	S7	S8
S3	0	0	0	0	0	0	0	0
S4	0	0	0	0	0	0	0	0
S5	0	0	0	0	0	0	0	0
S6	0	0	0	0	0	0	0	0
S7	0	0	0	0	0	0	0	0
S8	0	0	0	0	0	0	0	0
M1	216	1	1	1	1	1	1	1
M2	1	36	36	36	36	36	36	36
M3	1	36	36	6	6	6	6	6
M4	1	1	1	1	1	1	1	1
M5	1	1	1	1	1	1	1	1

Figure 4.15 Input Weight between Elements through Input Module



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	0	0	0	0	0	0	0	0	1296	1	1	1	1	1296	1296	1
2	0	0	0	0	0	0	0	0	1	36	36	6	1	1	1	6
3	0	0	0	0	0	0	0	0	1	36	36	6	1	1	1	6
4	0	0	0	0	0	0	0	0	1	36	6	6	1	1	1	36
5	0	0	0	0	0	0	0	0	1	36	6	36	1	1	1	36
6	0	0	0	0	0	0	0	0	1	36	6	6	1	1	1	6
7	0	0	0	0	0	0	0	0	1	36	6	6	1	1	1	6
8	0	0	0	0	0	0	0	0	1	36	6	6	1	1	1	6
9	1296	1	1	1	1	1	1	1	0	36	6	6	6	1	1	6
10	1	36	36	36	36	36	36	36	36	0	6	36	6	1	1	6
11	1	36	36	6	6	6	6	6	6	6	0	6	6	1	1	6
12	1	6	6	6	36	6	6	6	6	36	6	0	6	1	1	6
13	1	1	1	1	1	1	1	1	6	6	6	6	0	1	1	6
14	1296	1	1	1	1	1	1	1	1	1	1	1	1	0	1	6
15	1296	1	1	1	1	1	1	1	1	1	1	1	1	1	0	6
16	1	6	6	36	36	6	6	6	6	6	6	6	6	6	6	0

Figure 4.16 Input Weight between Elements through Excel File

The input of the aforementioned site layout planning data is organized and managed by an the user interface, as shown in Figure 4.17.

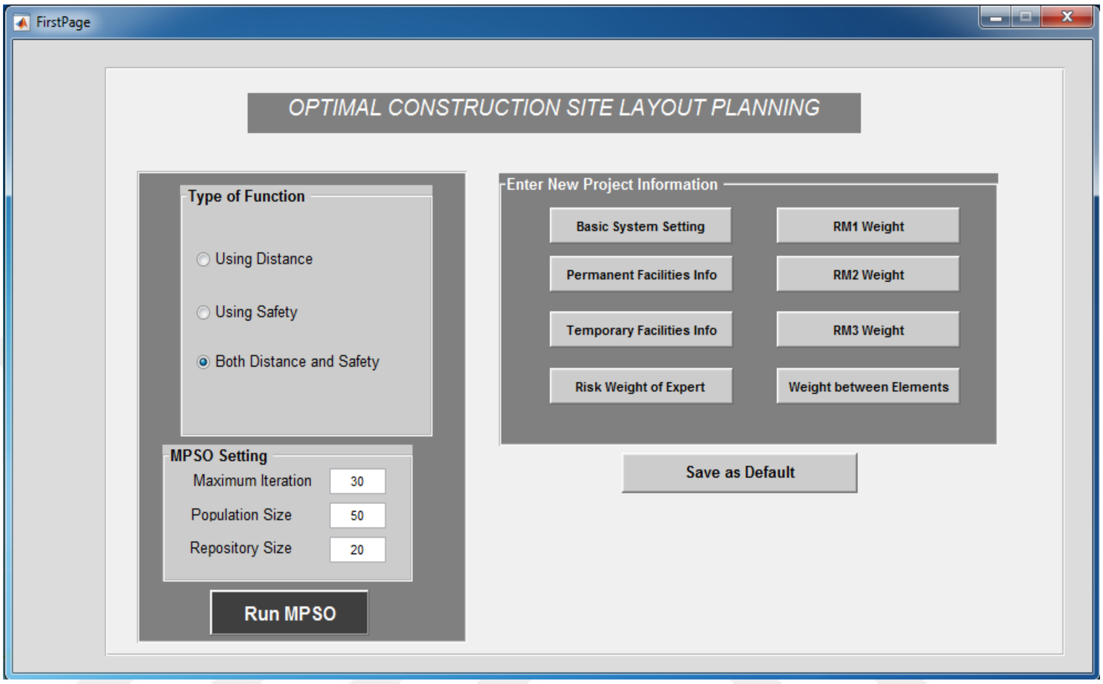


Figure 4.17. Optimization Control Module

By means of this interface, the users can choose the required optimization objectives. In this way, only the relevant data required for these objectives are entered. In addition, the input phase enables the input of multi-objective particle swarm optimization parameters. As shown in Figure 4.17, these parameters contain the iteration size, the population size, and repository size. These parameters can be determined specifically by the user optionally. These parameters are then used by the optimization module which can be invoked to initiate the optimization process by clicking on the “RUN MOPSO” button, as shown in Figure 4.17. Subsequent to completed the optimization process, the results are brought back and visualized in the output phase.

4.1.3.2. Output Phase

The output phase is designed to facilitate the retrieval of the optimal tradeoffs amongst (1) minimizing the risk of crane operations, and (2) minimizing the total distance of interaction. Besides, the output phase also can be used to recall the visualization module in order to help to visualize the optimal site layout plans by utilizing MATLAB software system, as shown in Figure 4.1

This phase is performed in two steps, which are designed to:

1. Retrieve the produced optimal tradeoff solutions and to display the Pareto optimal solutions, as shown in Figure 4.18.

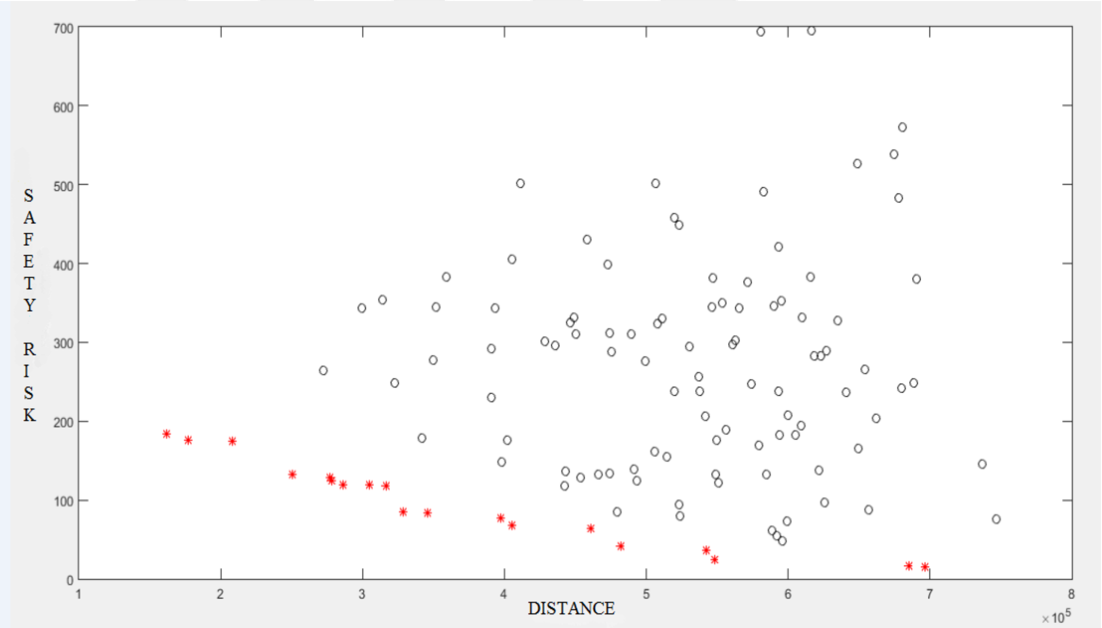


Figure 4.18 Pareto Optimal Solutions (An example of the case study).

The distribution of the Pareto optimal solutions (Red dots) is assumed favorable as shown in Figure 4.18.

It is unlikely to determine a certain point as an answer in solving the multi-objective problems. Because when we find a point where one of the target function is a minimum, there is another target function which is different than minimum at this point. For this reason, the answer for a multi-objective optimization problem is a curve rather than a point where every point is optimized with reference to just one of the objective functions.

2. Retrieve the created visual optimal site layout plans as shown in Figure 4.19.

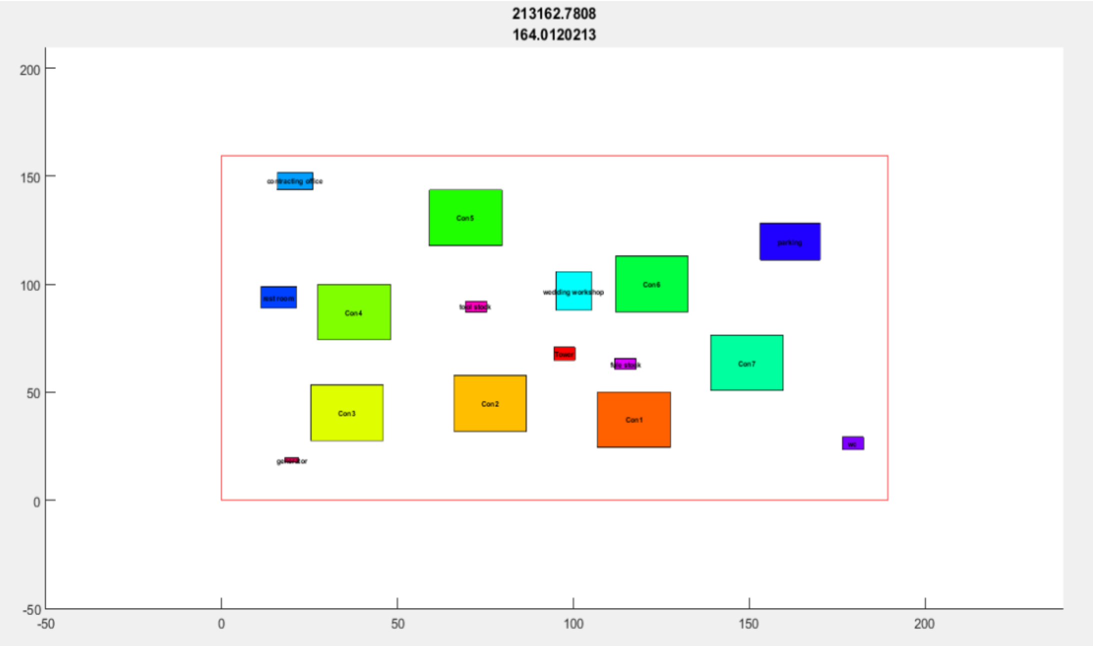


Figure 4.19. Optimal Site Layout Plans (An example of the case study).

In explanation of Figure 4.19, it should be added the axis X and Y which represent the length and width of the site, respectively. Besides, two numbers on the top of figure 4.19, which is in order from high to low, represent the total distance of interaction and the safety risk magnitude

3. Retrieve the generated site layout safety risk and distance data. as shown in Figure 4.20.

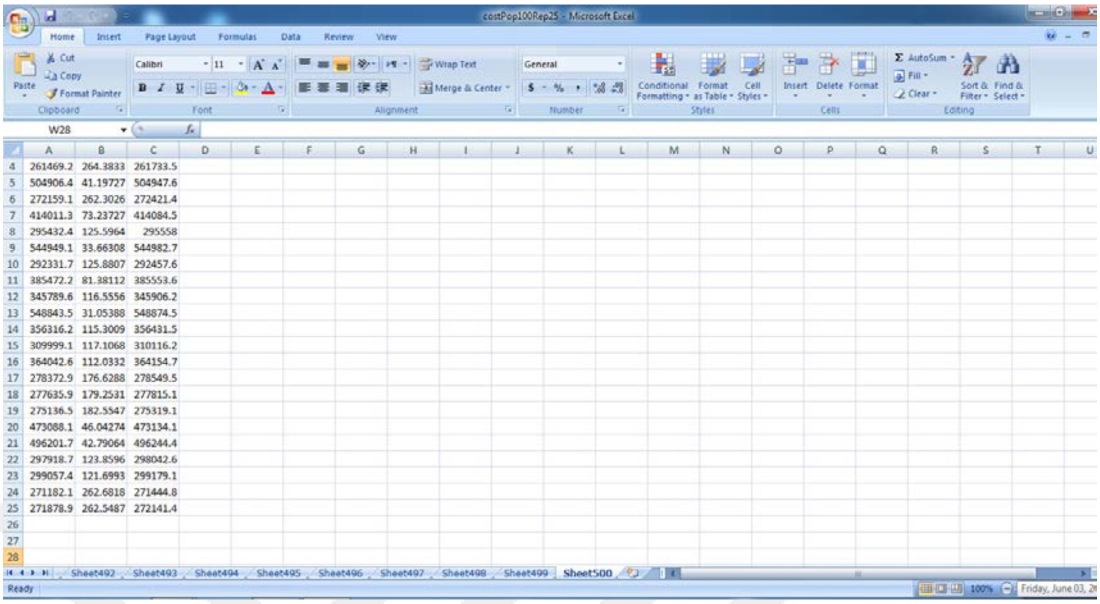


Figure 4.20. Site Layout Risk and Distance Data (An example of the case study).

In explanation of Figure 4.19, the columns A, B, and C which represent the site layout safety risk data, the site layout distance data and a total of two columns A and B respectively, should be added. The rows represent the size of the repository. On the other hand, the Excel sheets represent the number of iterations.

4. Retrieve the generated temporary facilities position data. As shown in Figure 4.21;

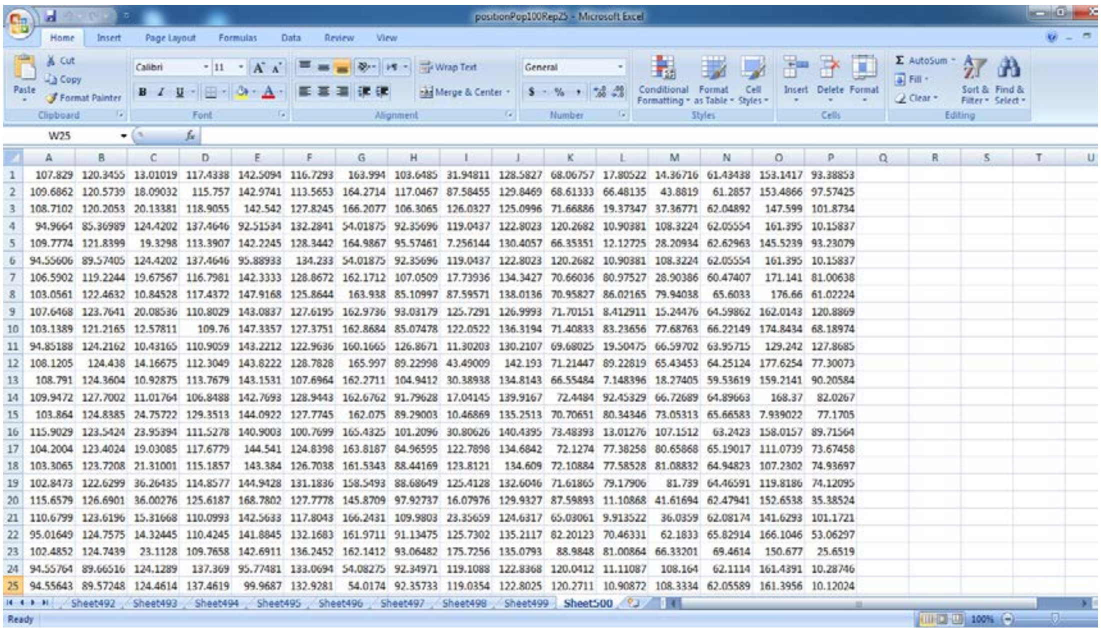


Figure 4.21. Temporary Facilities Position Data (An example of the case study).

In explanation of Figure 4.19, the columns representing the coordinate of a temporary facility should be added (e.g., the columns A and B in order to represent the coordinates X and Y as Welding workshop (F9), the columns C and D in order to represent coordinates X and Y as Contractor's office (F10), and etc.). The rows represent the repository size. Besides, Excel sheets also represent the number of the iterations.

4.2. Application Example

A comprehensive application example is analyzed to illustrate the competencies of the developed system in combining (1) minimization of the crane operations risk related to accidents in order to improve the safety level, and (2) minimization of the traveled total distance between the temporary facilities. In order to ensure the practicability of the developed model, real-life site layout planning data were obtained from an engineering team working on a residential building project. Input data of the application example are summarized in Tables 4.1 to 4.10.

Table 4.1 , 4.2, 4.3 present the dimension of the project site, the dimension of the tower crane, and optimization of the constraint information.

Table 4.1. Preject dimension

Length (m)	Width (m)
189.28	159.59

Table 4.2. Tower crane dimension

Height (m)	Jib length (m)
40	50

Table 4.3. Optimization constraints information

The maximum allowable proximity between the facilities and workshop boundary (m)	The maximum allowable proximity between the facilities (m)
1	1

Table 4.4 and 4.5 present the characteristics of permanent and temporary facilities that need to be located on site. While the proximity weights among facilities on the current site are summarized in Table 4.6, on the other hand, the weights of risk experts obtained from the literature are presented in Table 4.7.

Table 4.4. Permanent Facilities

Symbol		Facility Name	Length (m)	Width (m)	Location in site
F1		Tower crane	6	6	(94.44,64.83)
F2		Building 1	25.7	20.65	(106.88,24.50)
F3		Building 2	25.7	20.65	(65.95,32.05)
F4		Building 3	25.7	20.65	(25.30,27.70)
F5		Building 4	25.7	20.65	(27.30,74.20)
F6		Building 5	25.7	20.65	(59,117.94)
F7		Building 6	25.7	20.65	(111.93,87.30)
F8		Building 7	25.7	20.65	(138.98,50.8)

Table 4.5. Temporary Facilities

Symbol	Facility Name	Length (m)	Width (m)
F9	Welding workshop	10	18
F10	Contractor office	10	8
F11	Rest room	10	10
F12	Parking	17	17
F13	WC	6	6
F14	Fuel stock	6	5
F15	Tool stock	10	12
F16	Generator	2	2

Table 4.6. Proximity weight Facilities

	Facility (i)															
Facility (j)	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16
F1	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
F2	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-
F3	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-
F4	0	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-
F5	0	0	0	0	0	-	-	-	-	-	-	-	-	-	-	-
F6	0	0	0	0	0	0	-	-	-	-	-	-	-	-	-	-
F7	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-	-
F8	0	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-
F9	1296	1	1	1	1	1	1	1	0	-	-	-	-	-	-	-
F10	1	36	36	36	36	36	36	36	36	0	-	-	-	-	-	-
F11	1	36	36	6	6	6	6	6	6	6	0	-	-	-	-	-
F12	1	6	6	6	36	6	6	6	6	36	6	0	-	-	-	-
F13	1	1	1	1	1	1	1	1	6	6	6	6	0	-	-	-
F14	1296	1	1	1	1	1	1	1	1	1	1	1	1	0	-	-
F15	1296	1	1	1	1	1	1	1	1	1	1	1	1	1	0	-
F16	1	6	6	36	36	6	6	6	6	6	6	6	6	6	6	0

Note: — = equivalent values in this symmetric matrix.

Table 4.7. Weight of Risk Experts

Expert	Background	Weight
Expert 1	Project manager	0.25
Expert 2	Construction manager	0.22
Expert 3	Senior engineer	0.20
Expert 4	Site engineer with 15 years experience	0.18
Expert 5	Site engineer with 8 years experience	0.15
Total		0.25+0.22+0.20+0.18+0.15=1

Tables 4.8, 4.9 and 4.10 demonstrate the assessments of the experts related to the possibilities of the fatalities and the injuries based on the risks of crane loads and crane collapses.

Table 4.8. Experts assessments related to the possibility of the safety risks due to the strucks of tower crane loads on the temporary facilities

	Tower crane loads				
Facility	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
F1	0.4	0.8	0.4	0.6	0.6
F2	0.6	0.4	0.2	0.8	0.8
F3	1	0.4	0.2	0.4	0.4
F4	0.2	0.4	0.4	0.4	0.6
F5	0.2	0.4	0.2	0.4	0.4
F6	0.2	0.2	0.2	0.2	0.4
F7	0.2	0.4	0.4	0.2	0.4
F8	0.6	0.2	0.2	0.2	0.6

Table 4.9. Experts assessments related to the possibility of the safety risks due to the load falls from the tower crane on the temporary facilities

	Tower crane loads				
Facility	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
F1	0.4	0.8	0.6	0.6	0.8
F2	0.2	0.4	0.2	0.4	0.8
F3	0.2	0.4	0.2	0.4	0.8
F4	0.4	0.4	0.4	0.2	0.8
F5	0.2	0.4	0.2	0.4	0.4
F6	0.4	0.2	0.2	0.4	0.8
F7	0.4	0.2	0.4	0.2	0.8
F8	0.2	0.2	0.2	0.2	0.6

Table 4.10. Experts assessments related to the possibility of the safety risks due to the crane collapses on the temporary facilities

	Tower crane				
Facility	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
F1	0.4	0.8	0.6	0.6	0.8
F2	0.2	0.4	0.2	0.4	0.8
F3	0.2	0.4	0.2	0.4	0.8
F4	0.4	0.4	0.4	0.2	0.8
F5	0.2	0.4	0.2	0.4	0.4
F6	0.4	0.2	0.2	0.4	0.8
F7	0.4	0.2	0.4	0.2	0.8
F8	0.2	0.2	0.2	0.2	0.6

As shown in Figure 4.17, this data were input to the improved system by using the previously described user input interface which requires the construction planners in order to choose the required optimization objectives. According to the selected objectives, the planner can input all conveniently related data of the site layout planning and optimization, as seen in between Figure 4.2 and Figure 4.17. Afterward, these input data are stored in a number of tables in the relational database as seen in Figure 4.1. Finally, the optimization process starts and runs through a number of cycles. In this example, as shown in Figure 3.7, the system was run for 5 times (to increase the number of repetitions in stochastic approaches contributes to access the most reliable solutions) for each grid. Following the fulfillment of the optimization process, the planner can view:

1. The generated optimal tradeoff solutions and display the Pareto optimal solutions as shown in Figure 4.22.

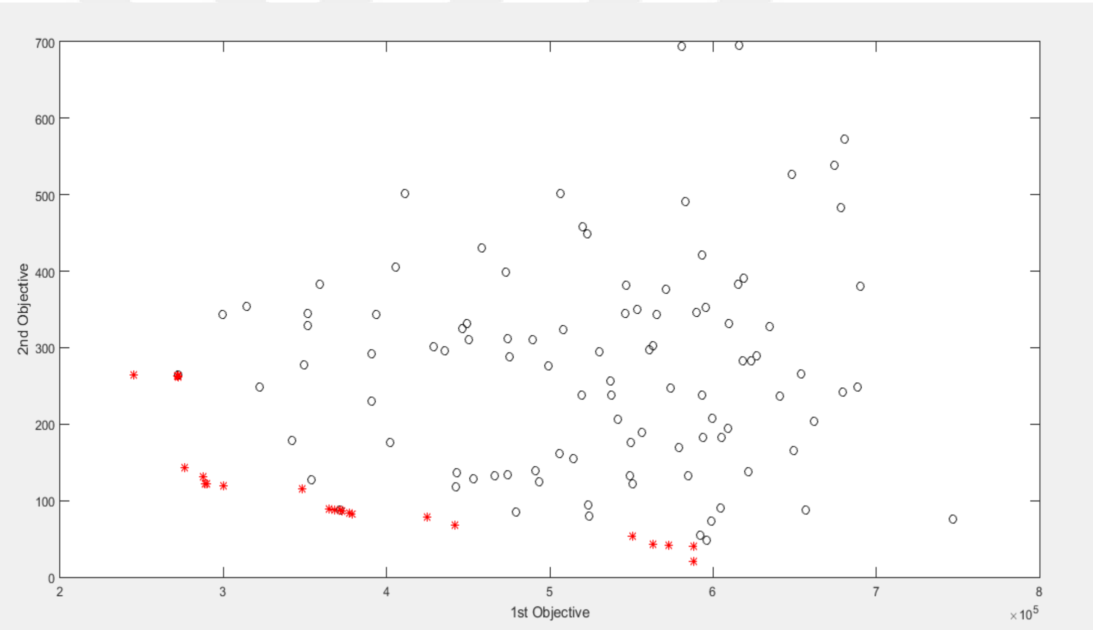


Figure 4.22 Pareto Optimal Solutions (An example of the case study)

2. The generated and visualized optimal site layout plans as shown in Figure 4.23.

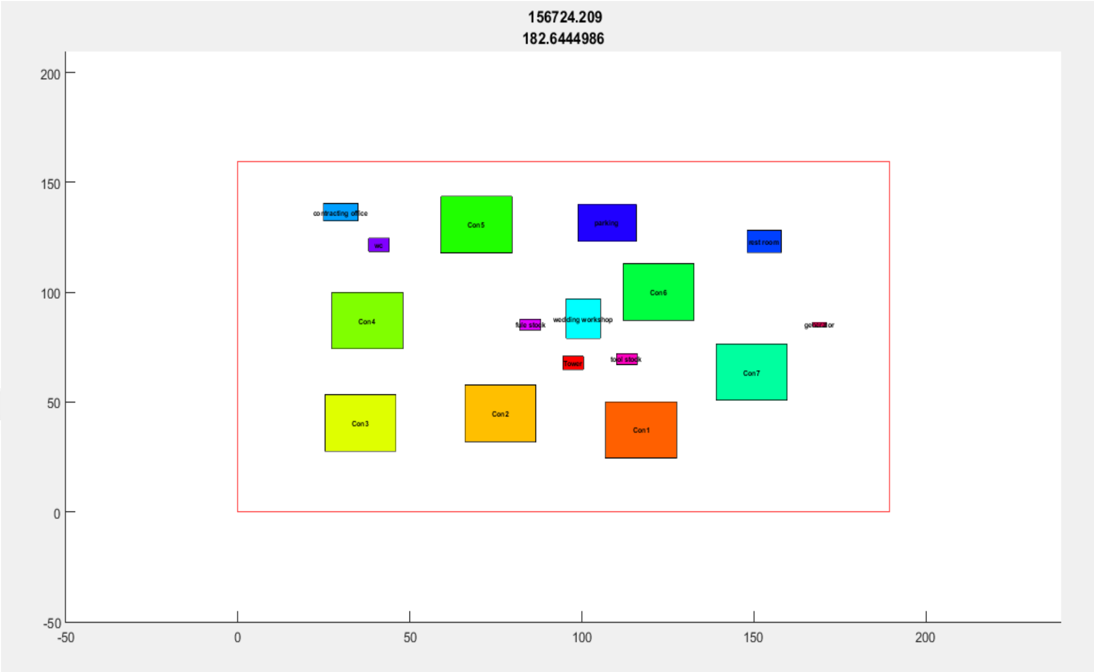
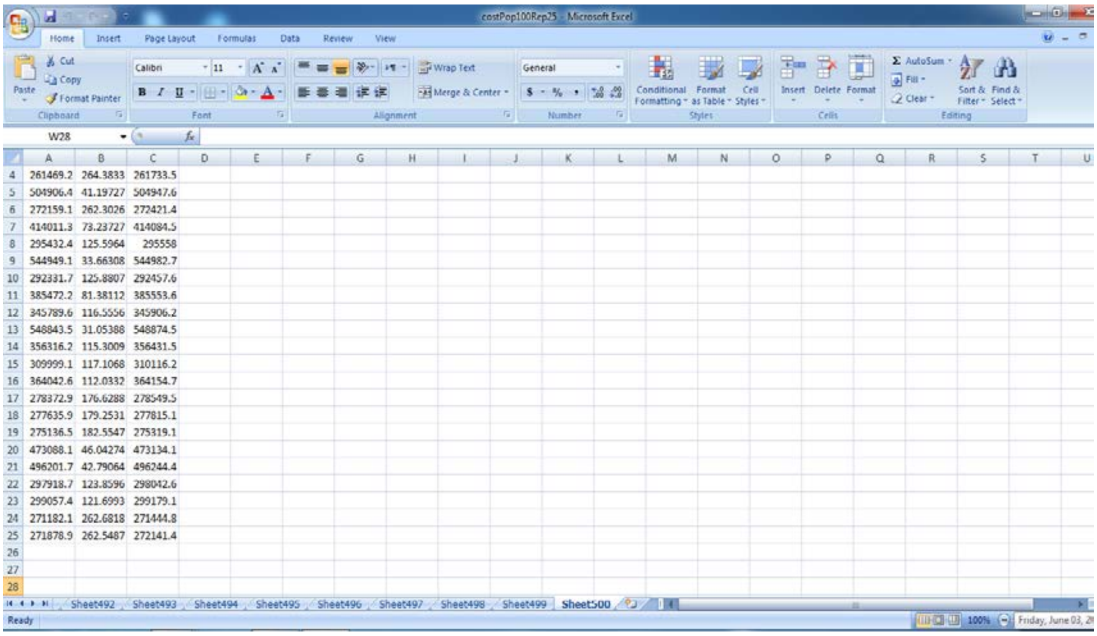


Figure 4.23 Optimal Site Layout Plans (An example of the case study)

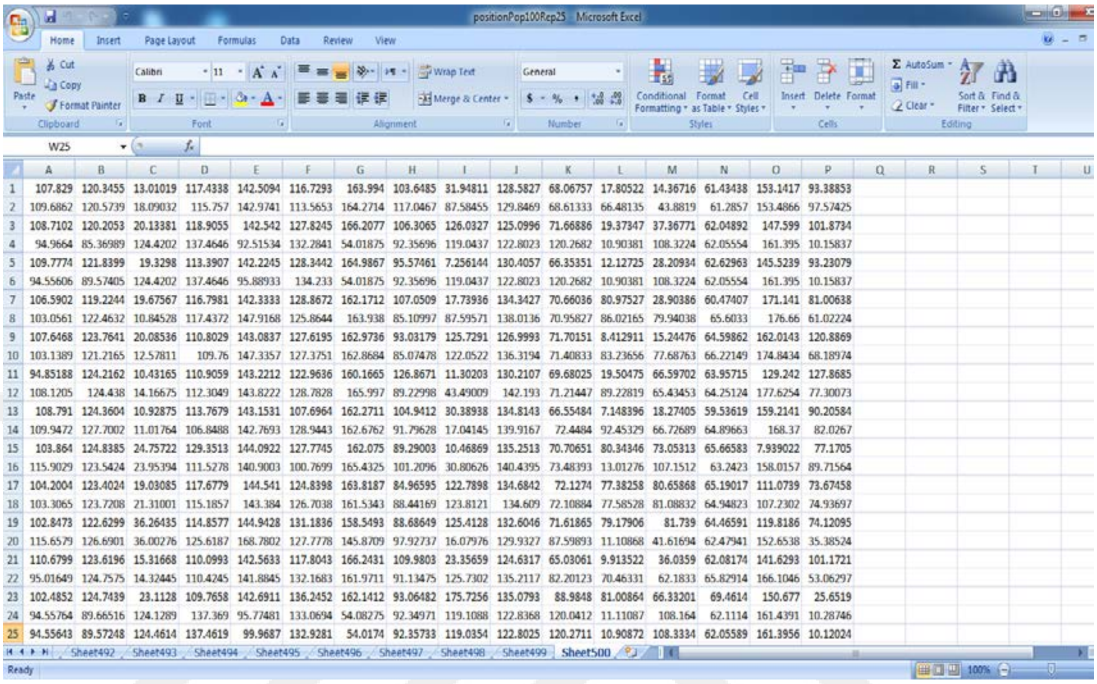
3. The generated site layout risk and distance data as shown in Figure 4.24.



	A	B	C
4	261469.2	264.3833	261733.5
5	504906.4	41.19727	504947.6
6	272159.1	262.3026	272421.4
7	414011.3	73.23727	414084.5
8	295432.4	125.5964	295558
9	544949.1	33.66308	544982.7
10	292331.7	125.8807	292457.6
11	385472.2	81.38112	385553.6
12	345789.6	116.5556	345906.2
13	548843.5	31.05388	548874.5
14	356316.2	115.3009	356431.5
15	309999.1	117.1068	310116.2
16	364042.6	112.0332	364154.7
17	278372.9	176.6288	278549.5
18	277635.9	179.2531	277815.1
19	275136.5	182.5547	275319.1
20	473088.1	46.04274	473134.1
21	496201.7	42.79064	496244.4
22	297918.7	123.8596	298042.6
23	299057.4	121.6993	299179.1
24	271182.1	262.6818	271444.8
25	271878.9	262.5487	272141.4

Figure 4.24 Site Layout Risk and Distance Data (An example of the case study)

4. Data of the generated temporary facilities position, as shown in Figure 4.25.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	107.829	120.3455	13.01019	117.4338	142.5094	116.7293	163.994	103.6485	31.94811	128.5827	68.06757	17.80522	14.36716	61.43438	153.1417	93.38853
2	109.6862	120.5739	18.09032	115.757	142.9741	113.5653	164.2714	117.0467	87.58455	129.8469	68.61333	66.48135	43.8819	61.2857	153.4866	97.57425
3	108.7102	120.2053	20.13381	118.9055	142.542	127.8245	166.2077	106.3065	126.0327	125.0996	71.66886	19.37347	37.36771	62.04892	147.599	101.8734
4	94.9664	85.36989	124.4202	137.4646	92.51534	132.2841	54.01875	92.35696	119.0437	122.8023	120.2682	10.90381	108.3224	62.05554	161.395	10.15837
5	109.7774	121.8399	19.3298	113.3907	142.2245	128.3442	164.9867	95.57461	7.256144	130.4057	66.35351	12.12725	28.20934	62.62963	145.5239	93.23079
6	94.55606	89.57405	124.4202	137.4646	95.88933	134.233	54.01875	92.35696	119.0437	122.8023	120.2682	10.90381	108.3224	62.05554	161.395	10.15837
7	106.5902	119.2244	19.67567	116.7981	142.3333	128.8672	162.1712	107.0509	17.73936	134.3427	70.66036	80.97527	28.90386	60.47407	171.141	81.00638
8	103.0561	122.4632	10.84528	117.4372	147.9168	125.8644	163.938	85.10997	87.59571	138.0136	70.95827	86.02165	79.94038	65.6033	176.66	61.02224
9	107.6468	123.7641	20.08536	110.8029	143.0837	127.6195	162.9736	93.03179	125.7291	126.9993	71.70151	8.412911	15.24476	64.59862	162.0143	120.8869
10	103.1389	121.2165	12.57811	109.76	147.3357	127.3751	162.8684	85.07478	122.0522	136.3194	71.40833	83.23656	77.68763	66.22149	174.8434	68.18974
11	94.85188	124.2162	10.43165	110.9059	143.2212	122.9636	160.1665	126.8671	11.30203	130.2107	69.68025	19.50475	66.59702	63.95715	129.242	127.8685
12	108.1205	124.438	14.16675	112.3049	143.8222	128.7828	165.997	89.22998	43.49009	142.193	71.21447	89.22819	65.43453	64.25124	177.6254	77.30073
13	108.791	124.3604	10.92875	113.7679	143.1531	107.6964	162.2711	104.9412	30.38938	134.8143	66.55484	7.148396	18.27405	59.53619	159.2141	90.20584
14	109.9472	127.7002	11.01764	106.8488	142.7693	128.9443	162.6762	91.79628	17.04145	139.9167	72.4484	92.45329	66.72689	64.89663	168.37	82.0267
15	103.864	124.8385	24.75722	129.3513	144.0922	127.7745	162.075	89.29003	10.46869	135.2513	70.70651	80.34346	73.05313	65.66583	7.939022	77.1705
16	115.9029	123.5424	23.95394	111.5278	140.9003	100.7699	165.4325	101.2096	30.80626	140.4395	73.48393	13.01276	107.1512	63.2423	158.0157	89.71564
17	104.2004	123.4024	19.03085	117.6779	144.541	124.8398	163.8187	84.96595	122.7898	134.6842	72.1274	77.38258	80.65868	65.19017	111.0739	73.67458
18	103.3065	123.7208	21.31001	115.1857	143.384	126.7038	161.5343	88.44169	123.8121	134.609	72.10884	77.58528	81.08832	64.94823	107.2302	74.93697
19	102.8473	122.6299	36.26435	114.8577	144.9428	131.1836	158.5493	88.68649	125.4128	132.6046	71.61865	79.17906	81.739	64.46591	119.8186	74.12095
20	115.6579	126.6901	36.00276	125.6187	168.7802	127.7778	145.8709	97.92737	16.07976	129.9327	87.59893	11.10868	41.61694	62.47941	152.6538	35.38524
21	110.6799	123.6196	15.31668	110.0993	142.5633	117.8043	166.2431	109.9803	23.35659	124.6317	65.03061	9.913522	36.0359	62.08174	141.6293	101.1721
22	95.01649	124.7575	14.32445	110.4245	141.8845	132.1683	161.9711	91.13475	125.7302	135.2117	82.20123	70.46331	62.1833	65.82914	166.1046	53.06297
23	102.4852	124.7439	23.1128	109.7658	142.6911	136.2452	162.1412	93.06482	175.7256	135.0793	88.9848	81.00864	66.33201	69.4614	150.677	25.6519
24	94.55764	89.66516	124.1289	137.369	95.77481	133.0694	54.08275	92.34971	119.1088	122.8368	120.0412	11.11087	108.164	62.1114	161.4391	10.28746
25	94.55643	89.57248	124.4614	137.4619	99.9687	132.9281	54.0174	92.35733	119.0354	122.8025	120.2711	10.90872	108.3334	62.05589	161.3956	10.12024

Figure 4.25 Temporary Facilities Position Data (An example of the case study)

4.3. Model evaluation and results verification

Model evaluation and results verification were performed by analyzing and testing the performance of the model in the application example (described in Section 4.2) are analyzed in order to illustrate the use of the present model and demonstrate its capabilities in between optimizing construction site layouts and generating optimal tradeoffs minimizing the risk of safety because of the crane operations and minimizing the total distance of interaction. Comparing experimentally of diverse optimization techniques always includes the concept of performance. The definition of quality is significantly more complicated for multi-objective optimization in comparison with single-objective optimization problems. Many metrics of performance exist which are used to measure the resulting non-dominated set in the Pareto-optimal front (Xu and Li 2012).

Two metrics of the performance were studied in this thesis for further expression of the efficiency of the convergence. (1) Calculating the mean of the obtained non-dominated front and (2) determining the minimum value for the resulting non-dominated set. Model runs compatibly with sets of grid search method by the number of 500 iterations and 5 repeats for each set (figure 3.7). They were performed to create the optimal tradeoffs between the construction safety and distance as well as to study the efficacy of the diversifying iterations size (it size), population sizes (pop size) and repository size (rep size) on the quality of the attained solutions by utilizing two metrics mentioned. It is confirmed in this thesis by the results of this analysis for the application example that increasing the iterations size lead to improved quality of the solution in the two metrics (see Figure 4.22 to 4.31).

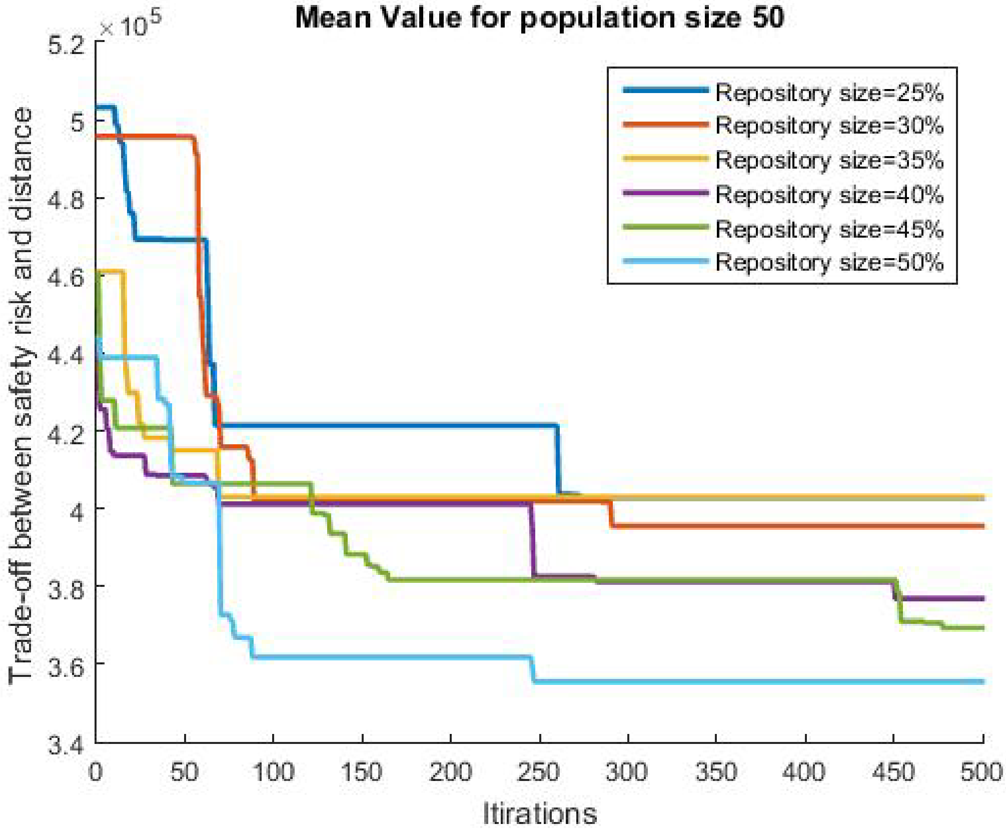


Figure 4.26 Mean Values for Population Size 50

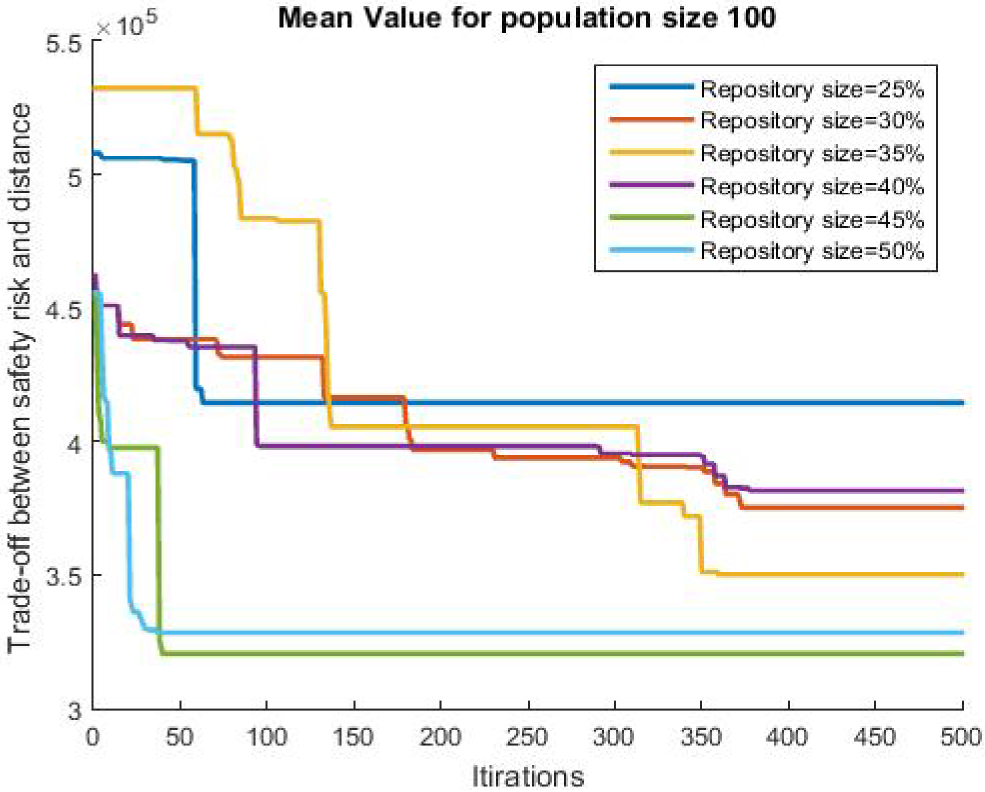


Figure 4.27 Mean Values for Population Size 100

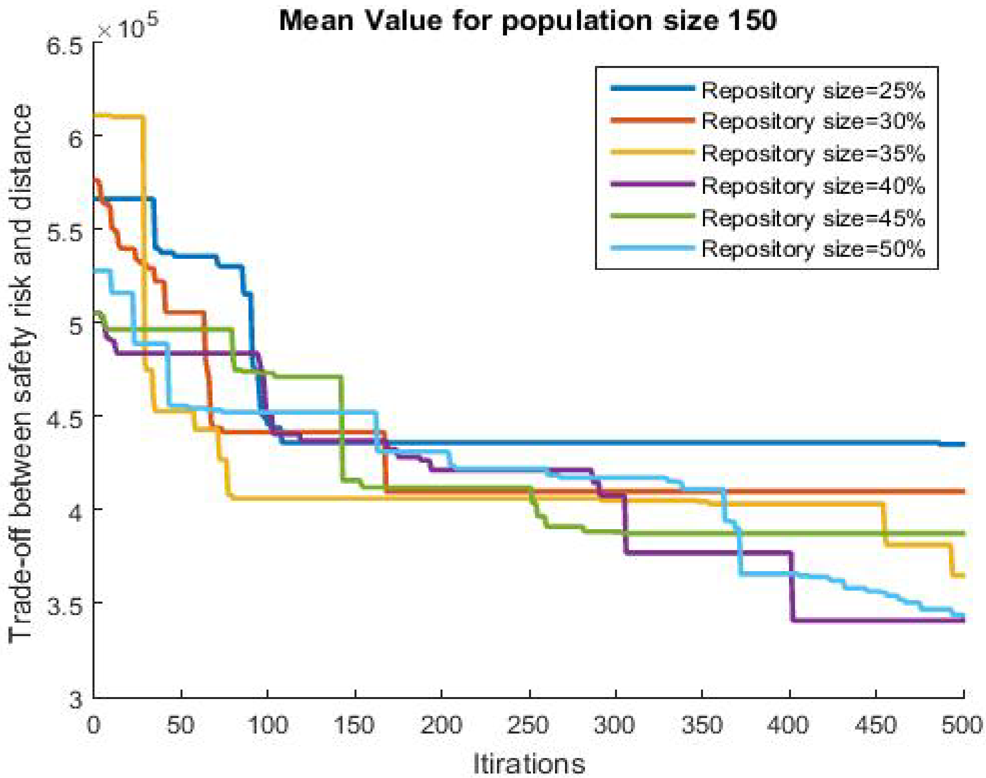


Figure 4.28 Mean Values for Population Size 150

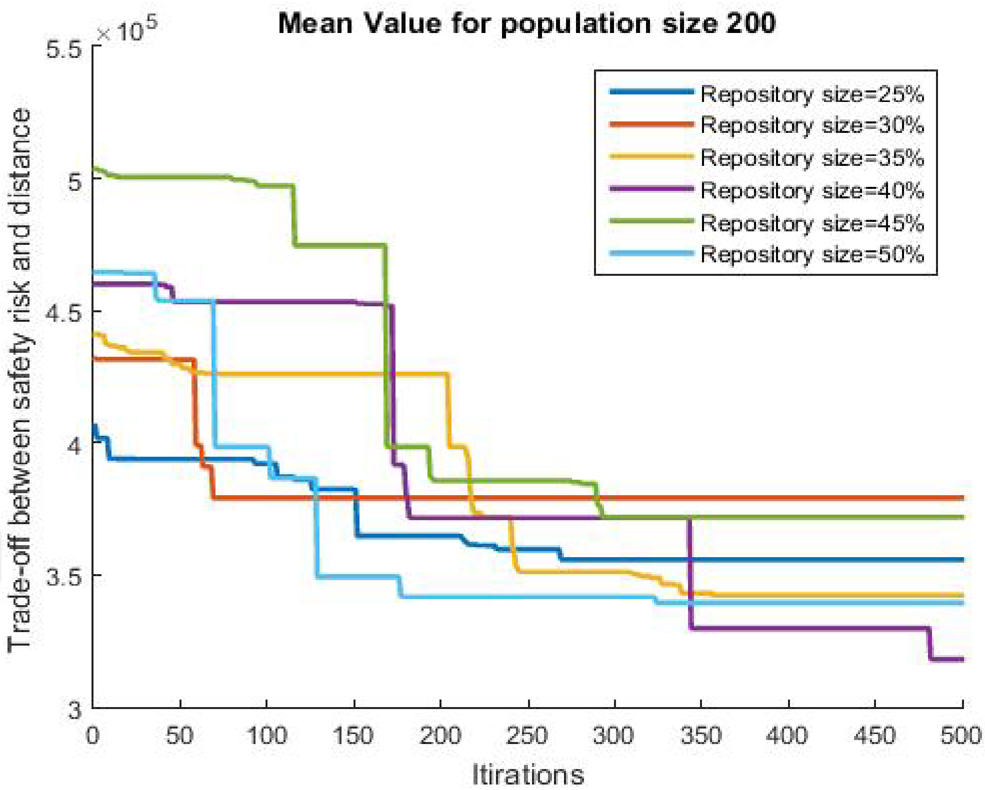


Figure 4.29 Mean Values for Population Size 200

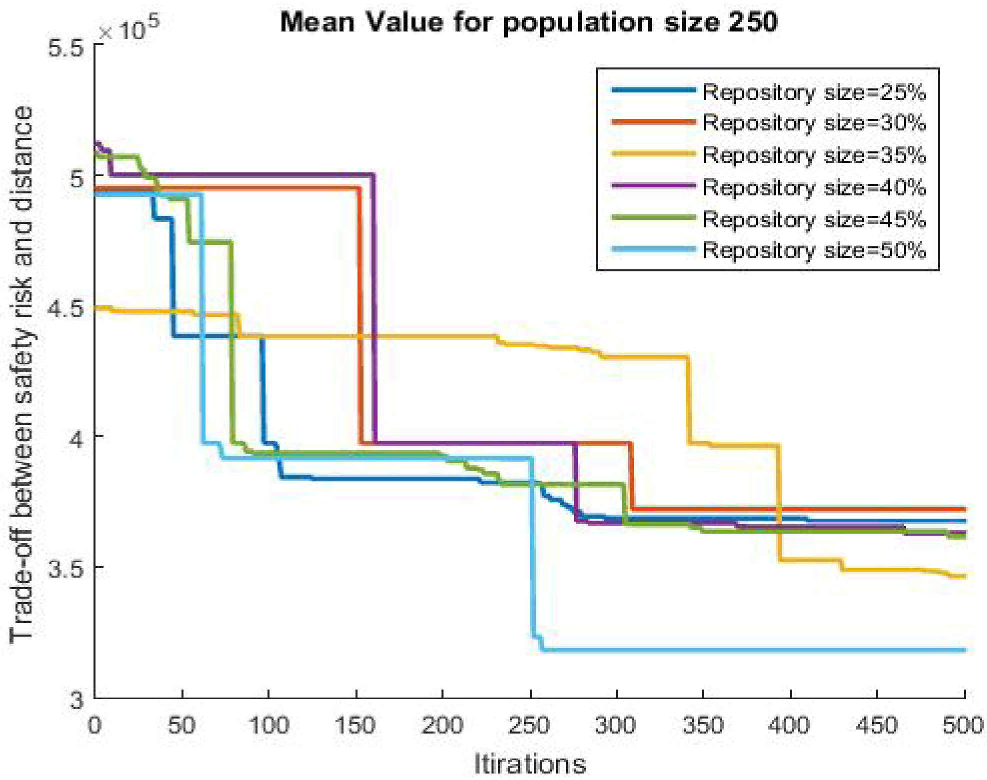


Figure 4.30 Mean Values for Population Size 250

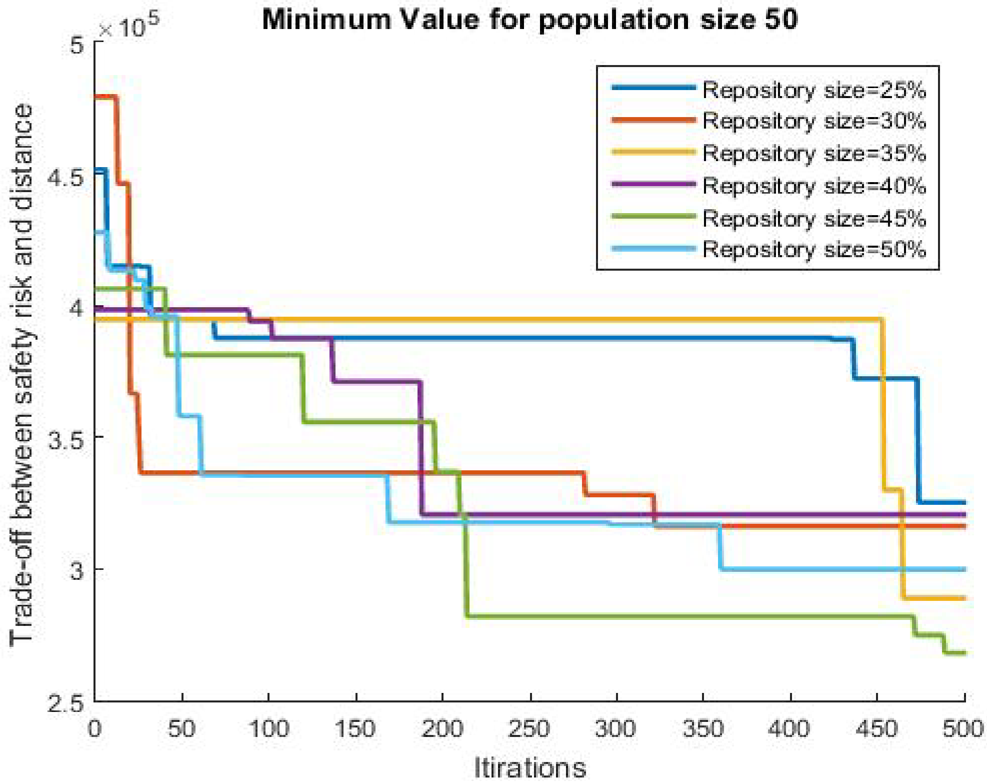


Figure 4.31 Minimum Values for Population Size 50

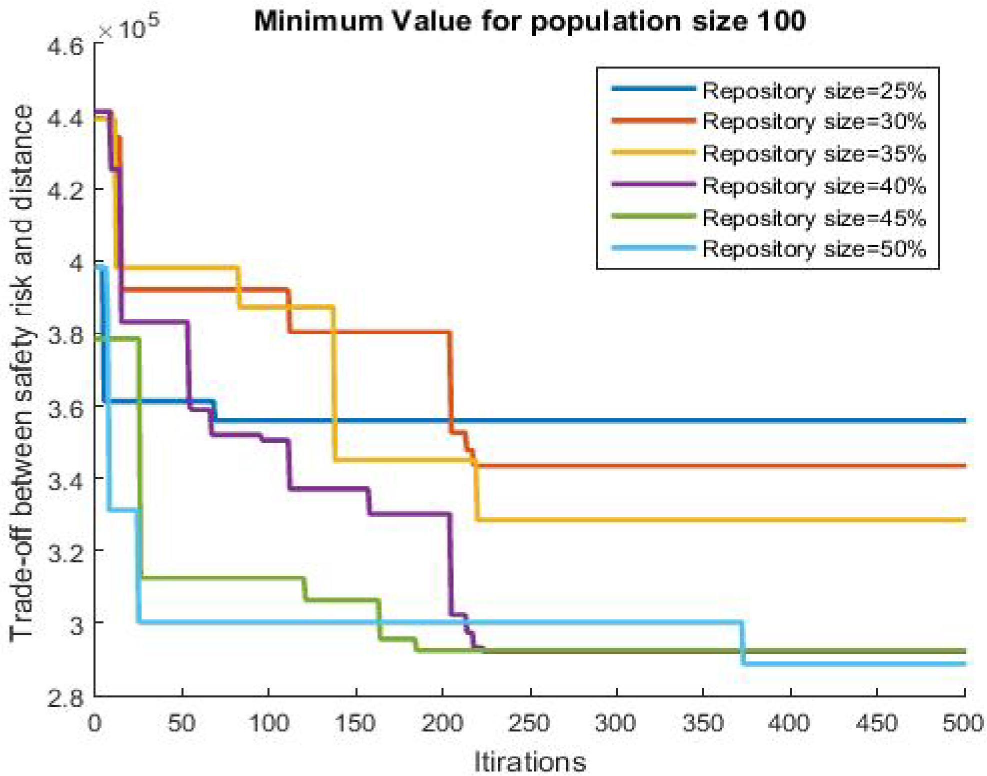


Figure 4.32 Minimum Values for Population Size 100

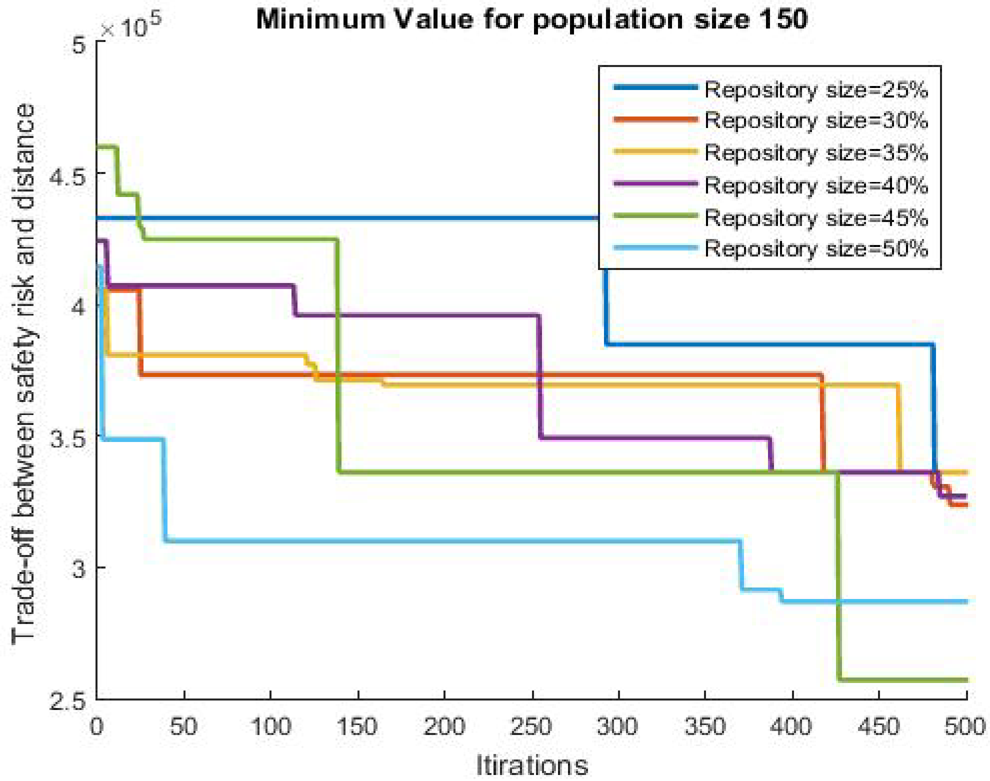


Figure 4.33 Minimum Values for Population Size 150

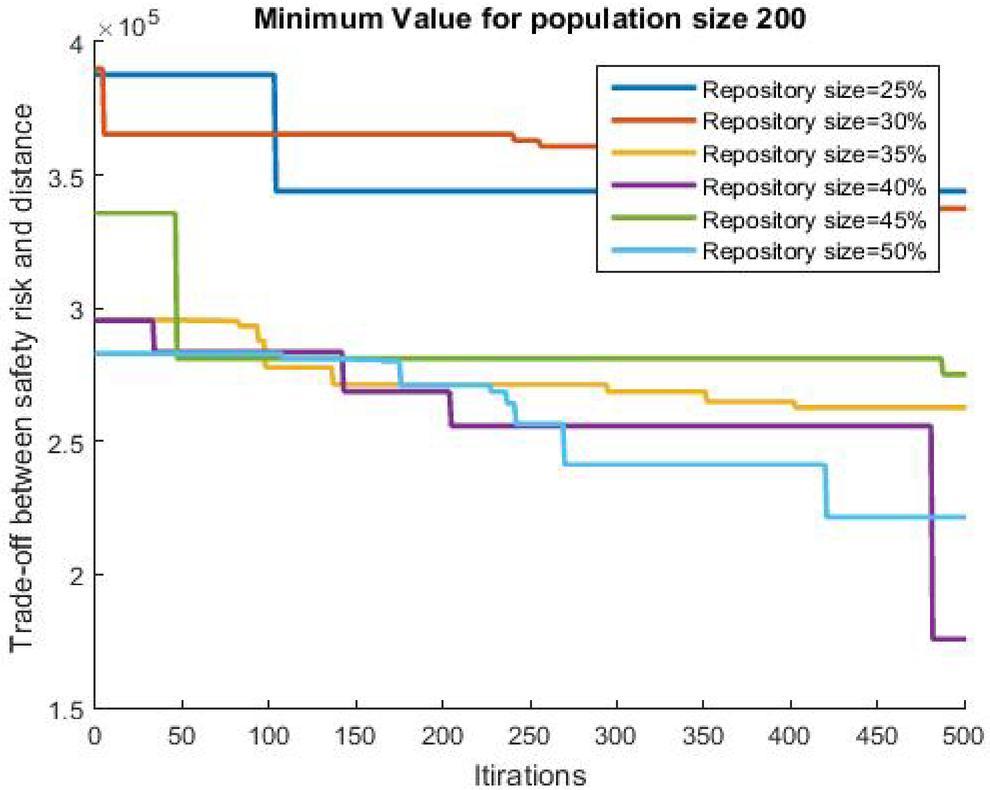


Figure 4.34 Minimum Values for Population Size 200

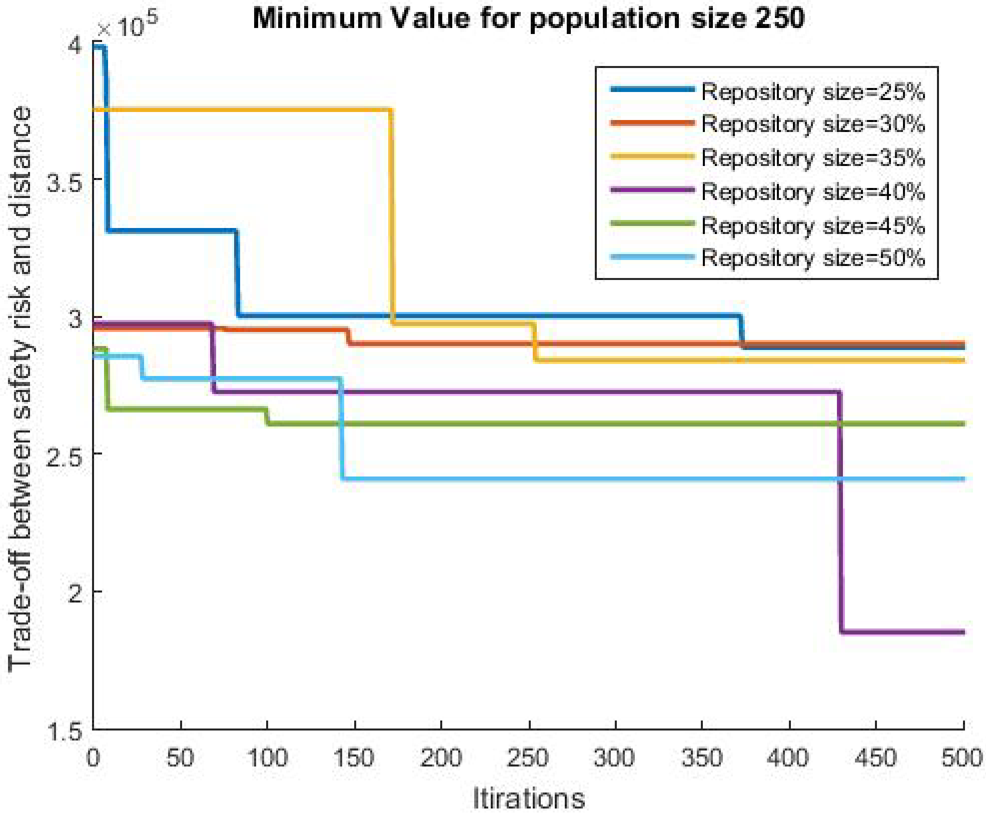


Figure 4.35 Minimum Values for Population Size 250

Moreover, the results emphasize that increasing the population sizes lead to improved quality of the solution in the two metrics.

Although some fluctuations happened in the two metrics, the final result has not been affected (see Figure 4.22 to 4.31). In addition, the results of this analysis also prove that increasing the repository size lead to improved quality of the solution in the two metrics. Although some fluctuations happened in the two metrics, the final result has not been affected (see Figure 4.22 to 4.31).

The generated optimal site layout solutions for any project will provide optimum tradeoffs between construction safety and distance of resources. For the current example, site layout A (see Figures 4.32 and 4.33) provides the worst risk of crane operations relevant safety risks in between non-dominated solutions (183.881692) as well as the best level of performance in total distance of interaction in between non-dominated solutions ($1.62021*10^5$). This risk level and the total distance of solution of solution A can be changed for the best level of risk performance in between non-dominated solutions (24.88126099) and the worst performance of total distance in between non-dominated solutions ($5.48430*10^5$), as shown in Figures 4.32 and 4.34 for the solution B. It should be noted that site layout A minimizes the total distance of interactions in between the resources on the site by (1) locating temporary facilities close to one another; and (2) shortening the travel distances between the facilities and the crane, as shown in Figure 4.33. In other respect, the site layout B minimizes entire construction risk on site by (1)locating highly risky temporary facilities (e.g., welding workshop, fuel stock, and tool stock) far from crane operations zones, (2)locating highly risk temporary facilities (e.g., welding workshop and fuel stock) far from each other, leading to the best level of risk performance (see Figure 4.34). The construction planners can evaluate these optimal tradeoffs between the construction risk and travel distance of resources as well as select a site layout which fulfills the specific requirements of the project being considered.

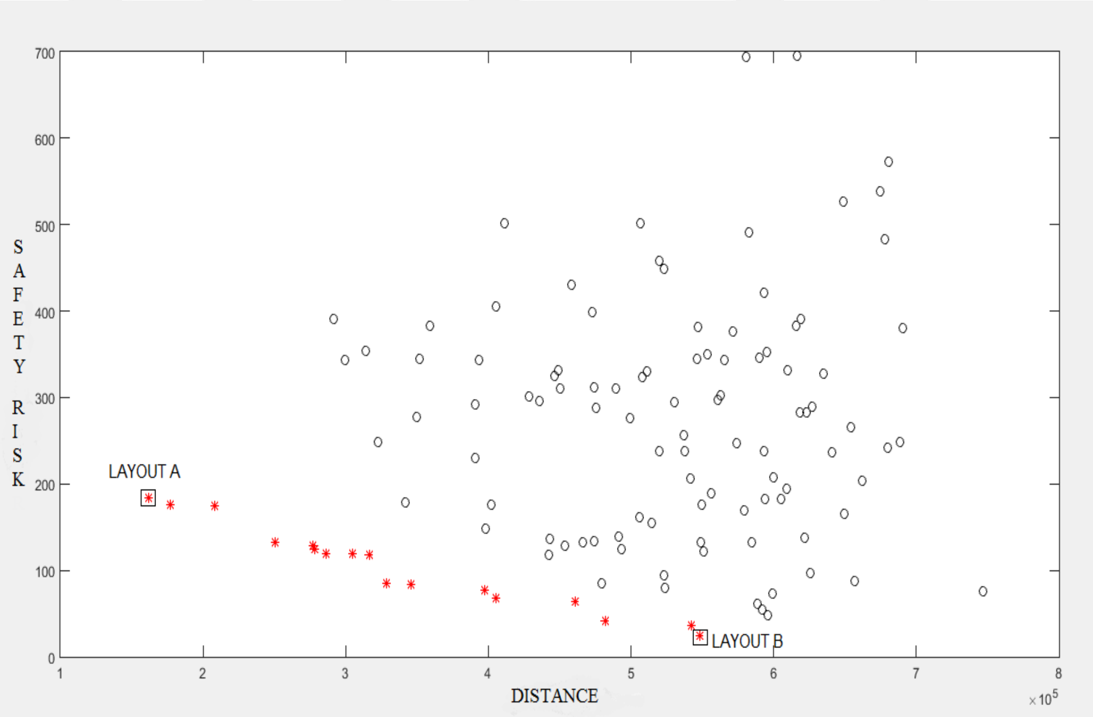


Figure 4.36 Pareto Optimal Solutions of the Example

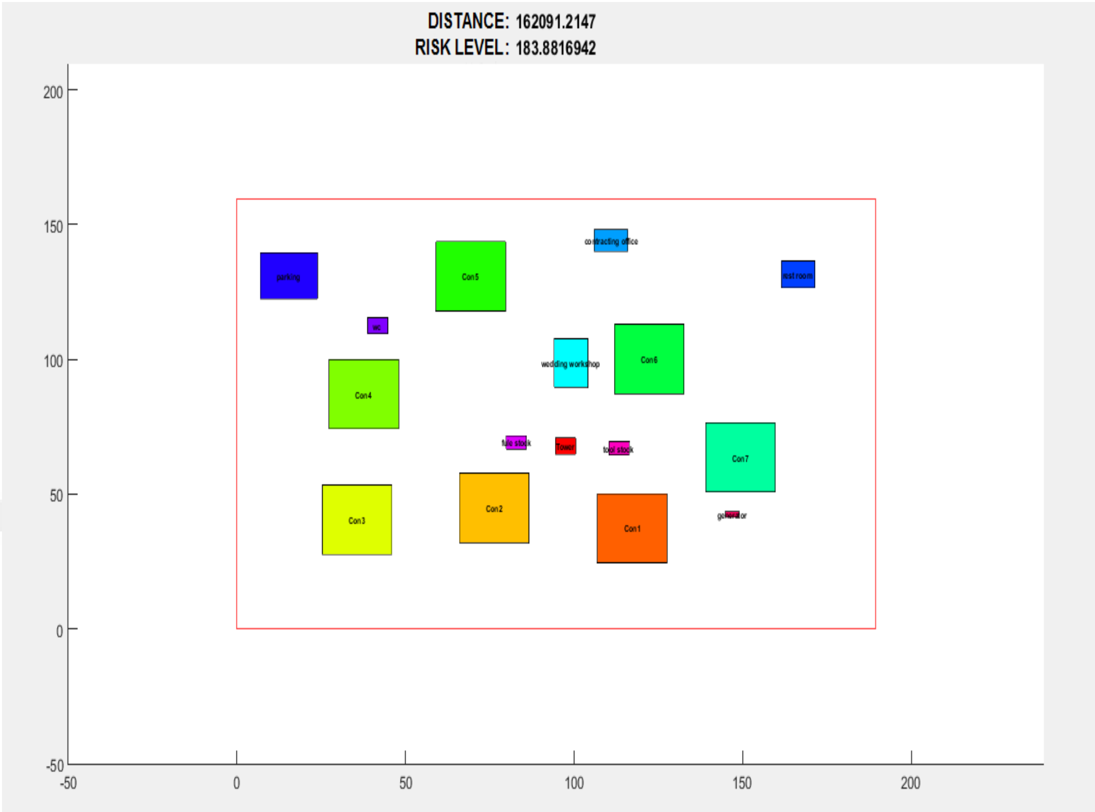
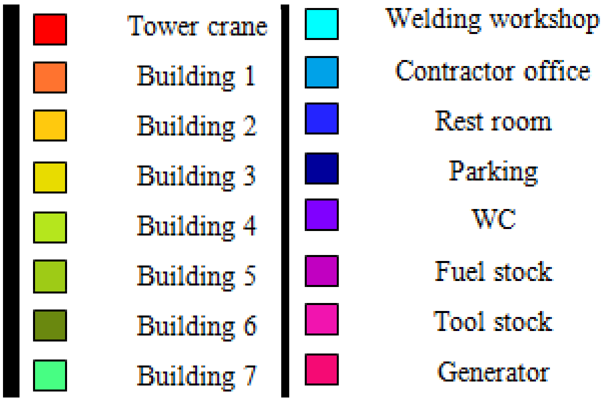


Figure 4.37 Layout A

Where



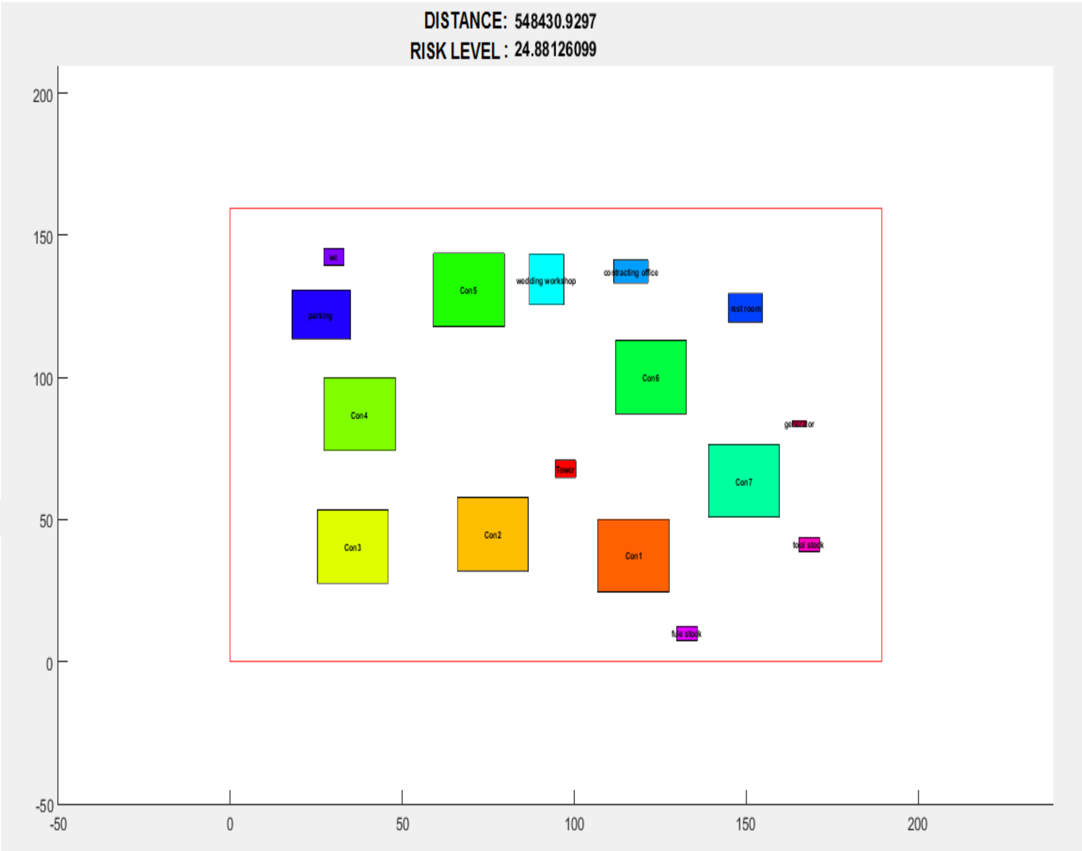


Figure 4.38 Layout B

Where

Tower crane	Welding workshop
Building 1	Contractor office
Building 2	Rest room
Building 3	Parking
Building 4	WC
Building 5	Fuel stock
Building 6	Tool stock
Building 7	Generator

5. CONCLUSIONS

The present research study was focused on multi-objective optimization of site layout planning for residential building projects (Khalafallah, 2006). In this study, new research developments involve (1) minimization of the safety risks of crane operations and (2) minimization of the total distance of interactions. The model is designed to search and generate optimal site layout plans that provide optimal tradeoffs in between these two important objectives satisfying all convenient constraints in this construction problem. The model has developed in five principal tasks: (1) Investigate and develop objective criteria to enable minimizing construction safety risk of crane operations; (2) Investigate and develop objective criteria to enable minimizing the total distance of interaction; (3) Modeling the site layout practical optimization constraints; (4) Implementing the model as a multi-objective particle swarm optimization algorithm application; and (5) Evaluating and verifying performance of the model by the grid search method. An application example was analyzed to illustrate its use and demonstrate its capabilities. The analysis results emphasize the new and unique capabilities and also prove the hypothesis that a new site layout planning model can be developed to search and determine the optimal tradeoffs between minimizing the safety risk of crane operations and minimize the total distance of interaction of resources on the site, while satisfying all the practical site layout constraints. The system is designed not only to optimize the above-mentioned objectives, but also to enable supporting improved visualization of the generated optimal site layout solutions. The primary research developments of this study contribute to the improvement of current practices in construction site layout planning and can lead to a competitive advantage for contractors utilizing the developed system due to (1) increasing the efficiency of construction operations and (2) decreasing the insurance premiums, in consequence of these safety improvements.

Although the current study showed that the developed model;

1. Considers user-defined variables such as the size of the site, type and number of the temporary facilities, the relationship between these facilities from the point of safety and traveling distance, the relationship between the crane and the temporary facilities, risk factors and variables required by the optimization algorithm.
2. Presents an automated system for the construction planners. That system provides a variety of different solutions as well as site layout plans that can be practically utilized on the site.

There are two limitations of this current model because it is only convenient for quadrilateral construction sites and for one tower crane. For this reason, the number of additional research directions has been determined during the course of this study. This includes:

1. Development of a model that covers any site shape.
2. Development of a model for more than one tower crane.

Additional developments are also recommended as;

3. Including security and environmental requirements as optimization objectives,
4. Using various approaches of artificial intelligence in order to generate optimal site layout plans in construction projects and compare the results.

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CURRICULUM VITAE

He was born in Bonab, Iran on 30.12.1982. He graduated from High School. He began his undergraduate studies in the Civil Engineering Department of Islamic Azad University and has completed university studies in the same department in 2006. In the same year, he began to work as a civil engineer at a construction company in Tehran and continued to work until 2010.

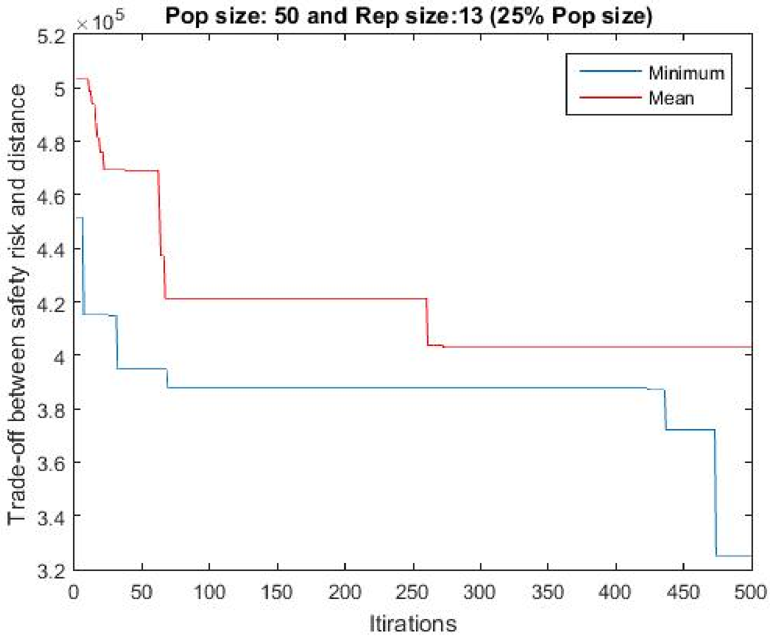
For continuation of his education, he came to Turkey and he began to graduate studies in the Department of Civil Engineering, Institute of Science and Technology of Cukurova University in the same year. He completed his graduate studies in 2012 by successfully defending the thesis titled “Radio Frequency Identification System (RFID) –Facilitated Construction Materials Management (RFID-CMM)”.

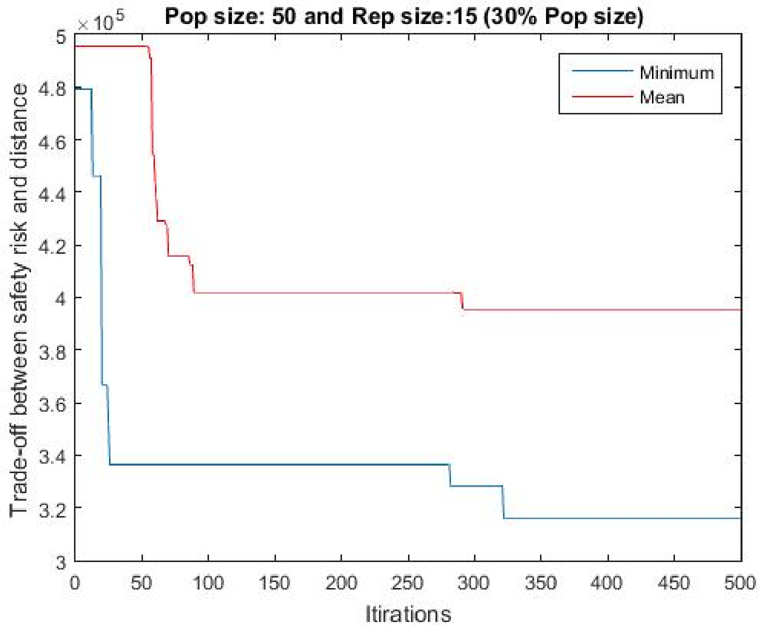
In 2013, he started his Ph.D. studies in the same department and university. Siamak BAZAATİ who is married, knows English, Persian, Azerbaijani, and Turkish.

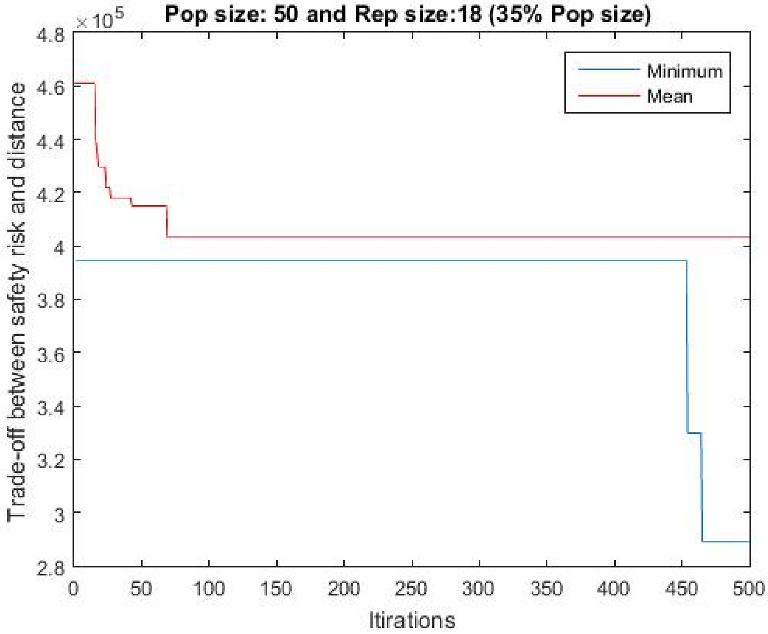
APPENDIX

APPENDIX 1: THE RESULTS FOR THE APPLICATION EXAMPLE

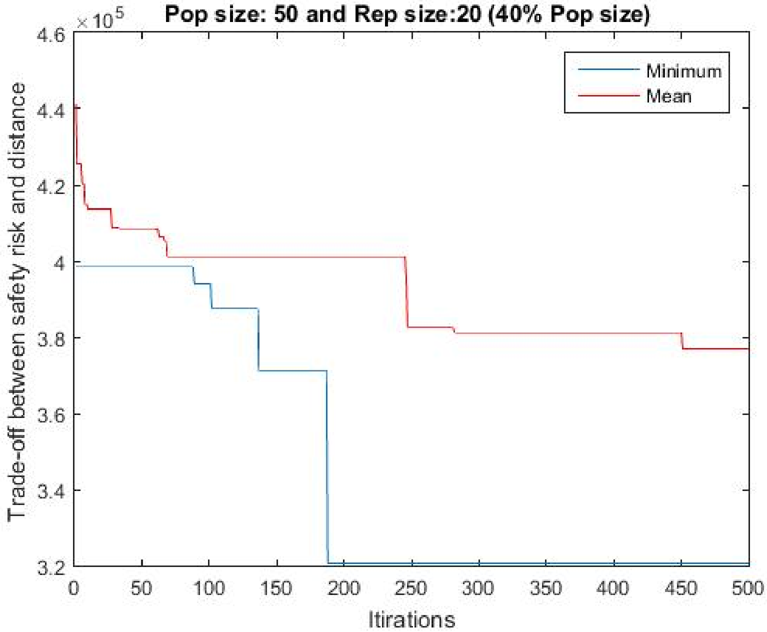
1. Mean and Minimum Values for Population Size 50 and Repository Size 25%, 30%, 35%, 40%, 45% and 50%



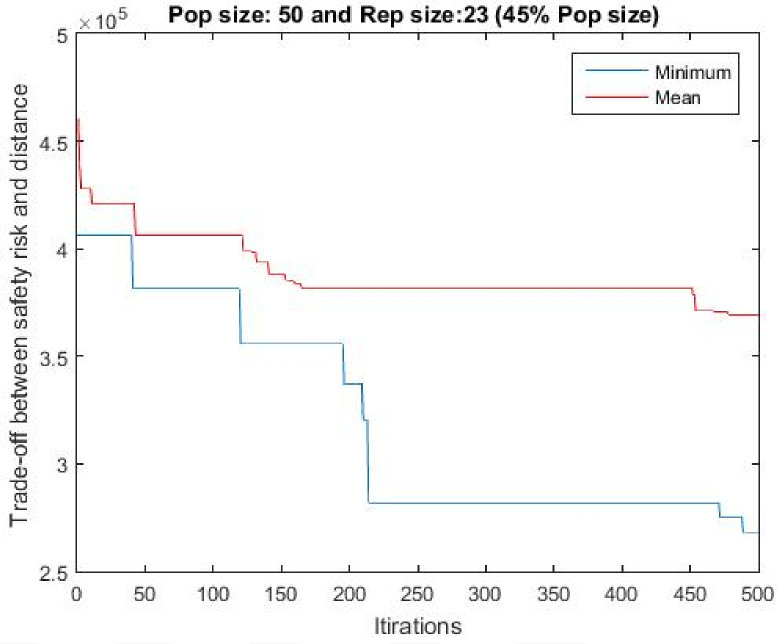


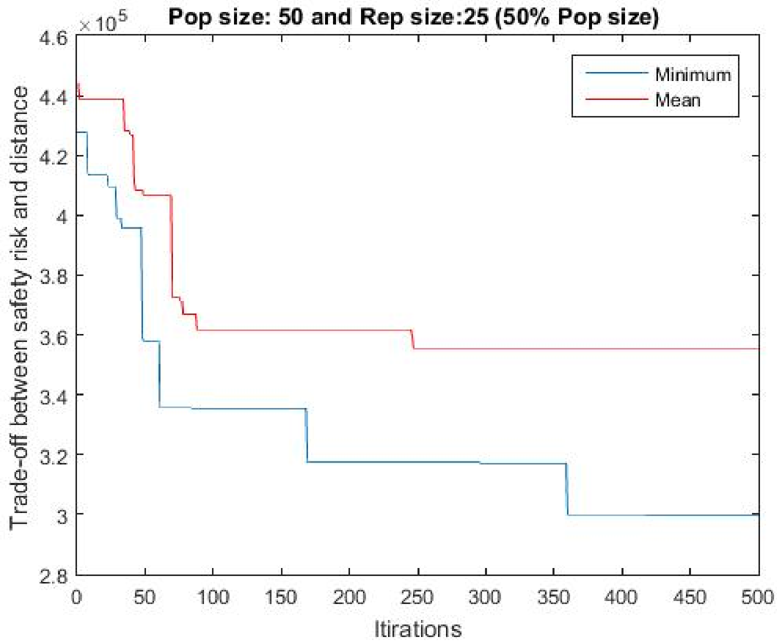


Pop size: 50 and Rep size:18 (35% Pop size)
×10^5
Trade-off between safety risk and distance
Itirations
Minimum
Mean
4.8
4.6
4.4
4.2
4
3.8
3.6
3.4
3.2
3
2.8
0
50
100
150
200
250
300
350
400
450
500

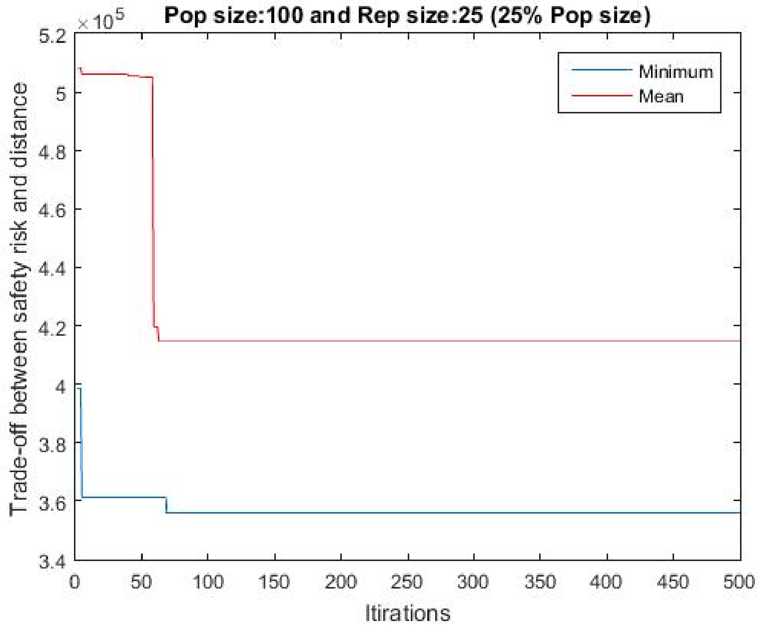


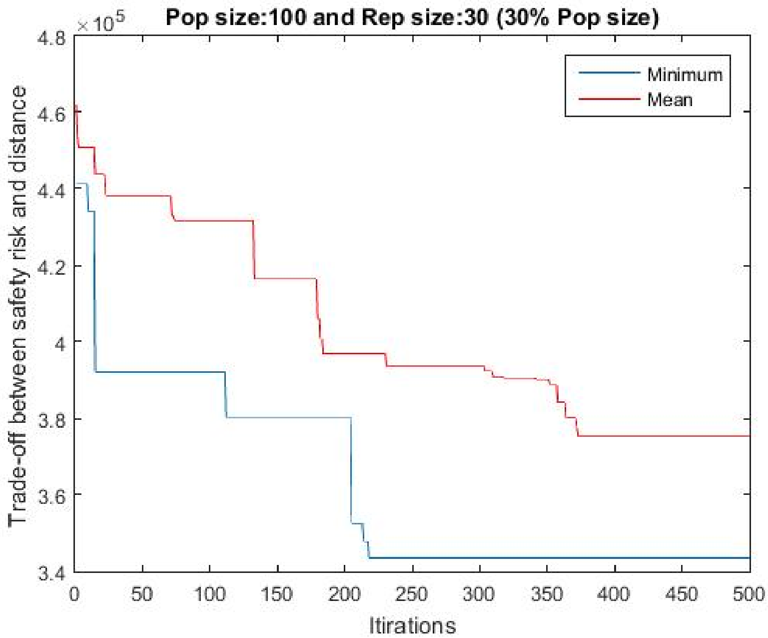
Pop size: 50 and Rep size:20 (40% Pop size)
×10^5
Trade-off between safety risk and distance
Itirations
Minimum
Mean
4.6
4.4
4.2
4
3.8
3.6
3.4
3.2
0
50
100
150
200
250
300
350
400
450
500

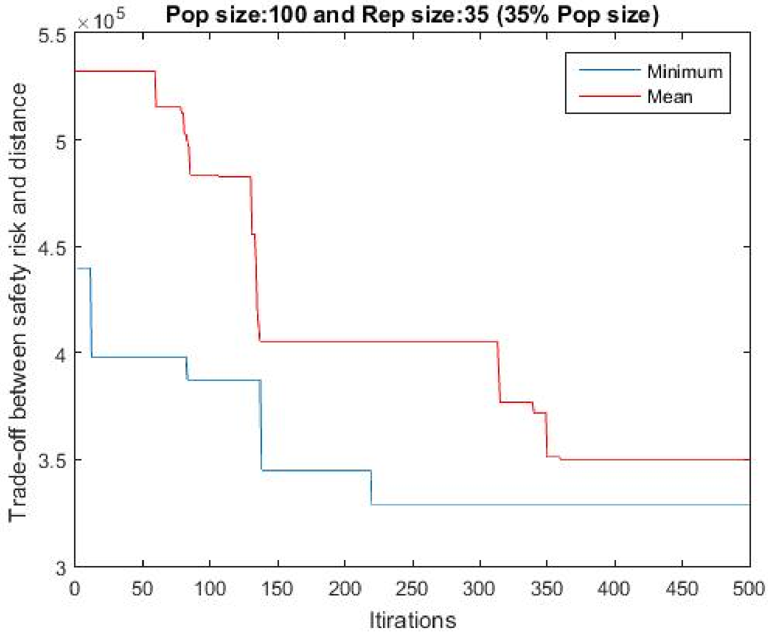

Pop size: 50 and Rep size:23 (45% Pop size)
×10^5
Trade-off between safety risk and distance
Itirations
Minimum
Mean
2.5
3
3.5
4
4.5
5
0
50
100
150
200
250
300
350
400
450
500


Pop size: 50 and Rep size:25 (50% Pop size)
×10^5
Trade-off between safety risk and distance
Itirations
Minimum
Mean
2.8
3
3.2
3.4
3.6
3.8
4
4.2
4.4
4.6
0
50
100
150
200
250
300
350
400
450
500

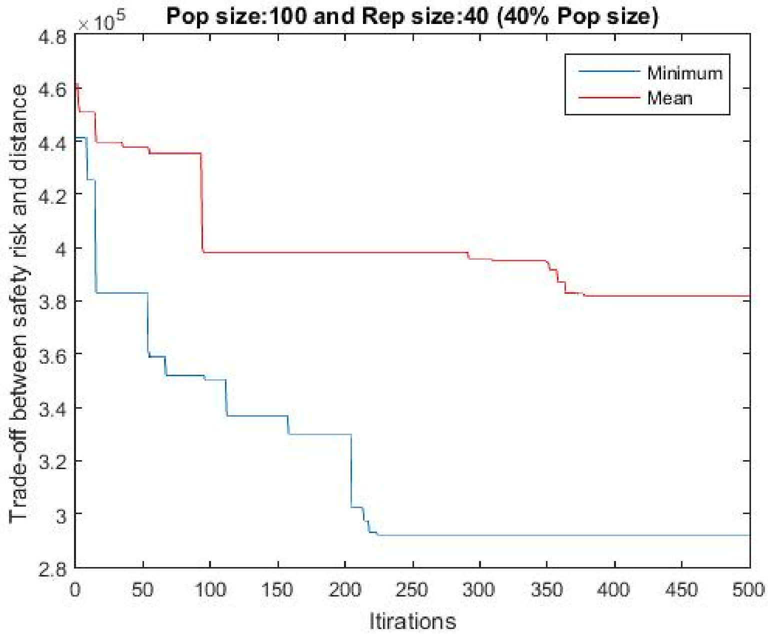
2. Mean and Minimum Values for Population Size 100 and Repository Size 25%, 30%, 35%, 40%, 45% and 50%



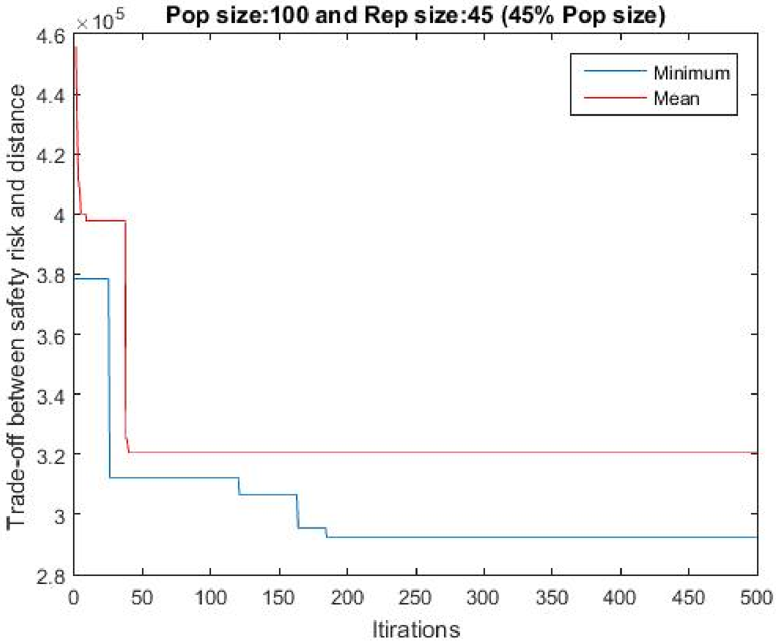


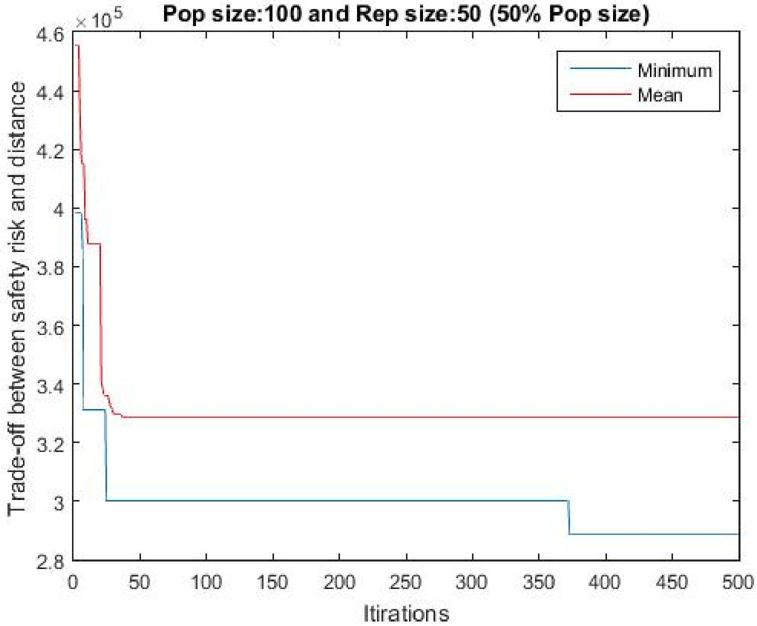


Pop size:100 and Rep size:35 (35% Pop size)
×10^5
5.5
5
4.5
4
3.5
3
0
50
100
150
200
250
300
350
400
450
500
Itirations
Trade-off between safety risk and distance
Minimum
Mean

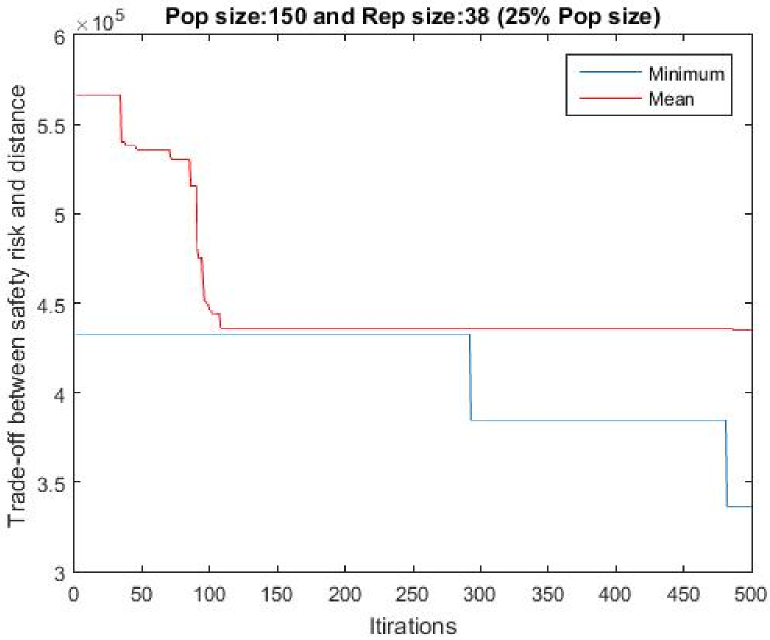


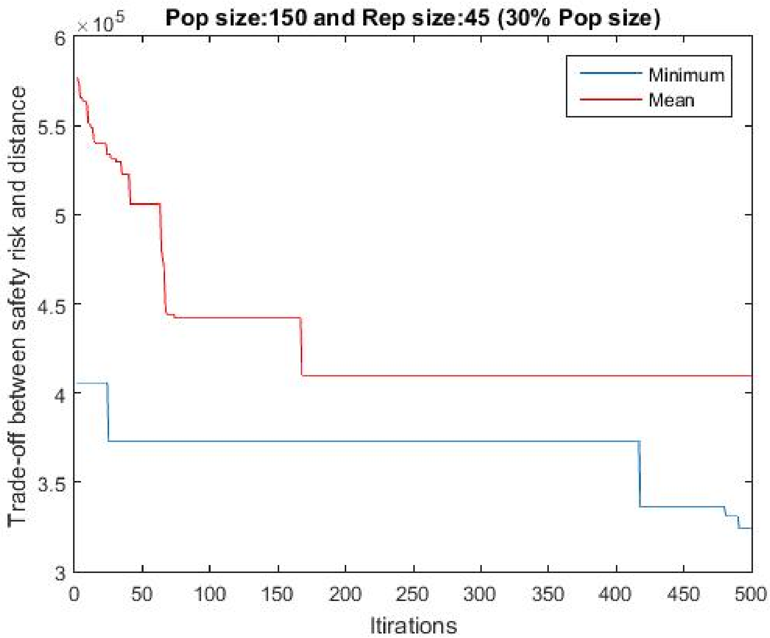
Pop size:100 and Rep size:40 (40% Pop size)
×10^5
4.8
4.6
4.4
4.2
4
3.8
3.6
3.4
3.2
3
2.8
0
50
100
150
200
250
300
350
400
450
500
Itirations
Trade-off between safety risk and distance
Minimum
Mean

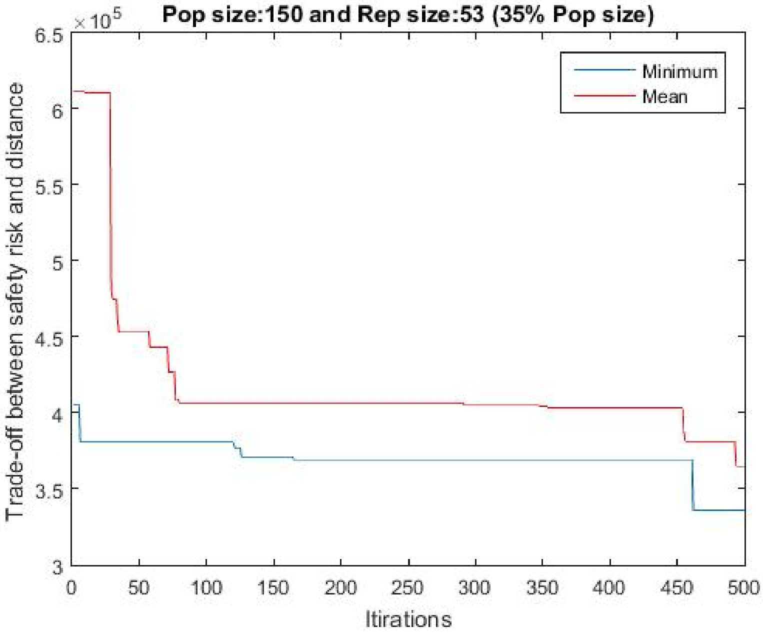

Pop size:100 and Rep size:45 (45% Pop size)
×10^5
4.6
4.4
4.2
4
3.8
3.6
3.4
3.2
3
2.8
Trade-off between safety risk and distance
0
50
100
150
200
250
300
350
400
450
500
Itirations
Minimum
Mean

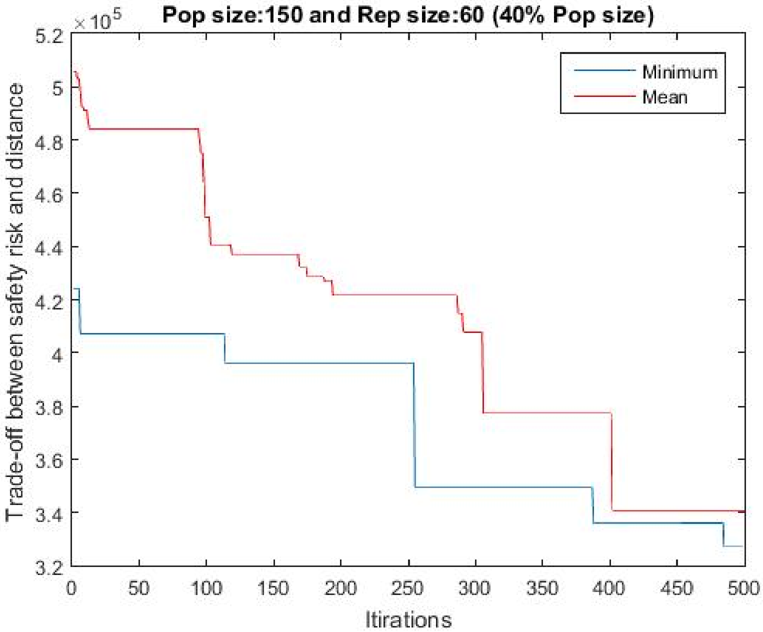

Pop size:100 and Rep size:50 (50% Pop size)
×10^5
4.6
4.4
4.2
4
3.8
3.6
3.4
3.2
3
2.8
Trade-off between safety risk and distance
0
50
100
150
200
250
300
350
400
450
500
Itirations
Minimum
Mean

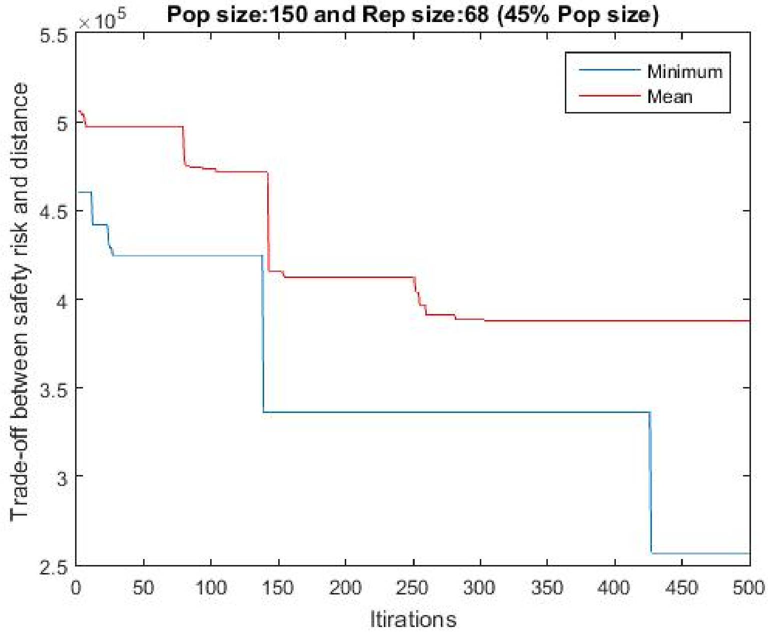
3. Mean and Minimum Values for Population Size 150 and Repository Size 25%, 30%, 35%, 40%, 45% and 50%

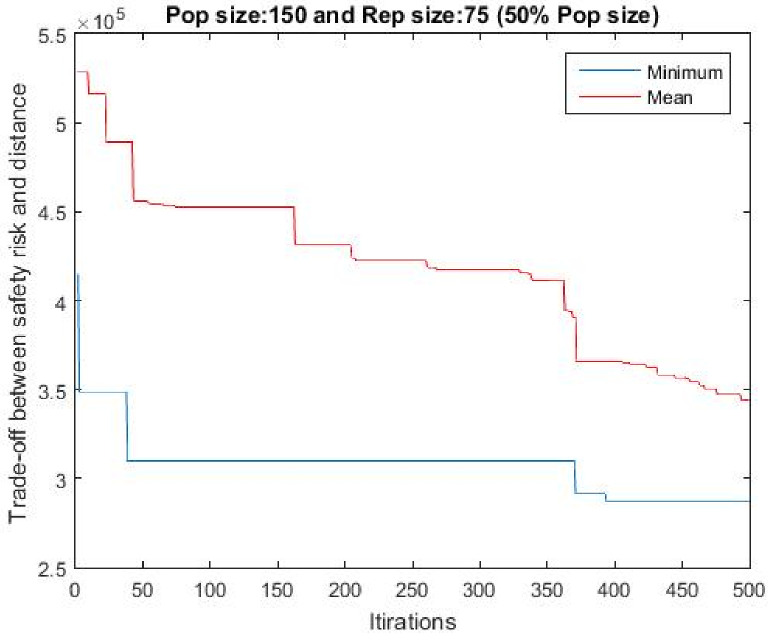




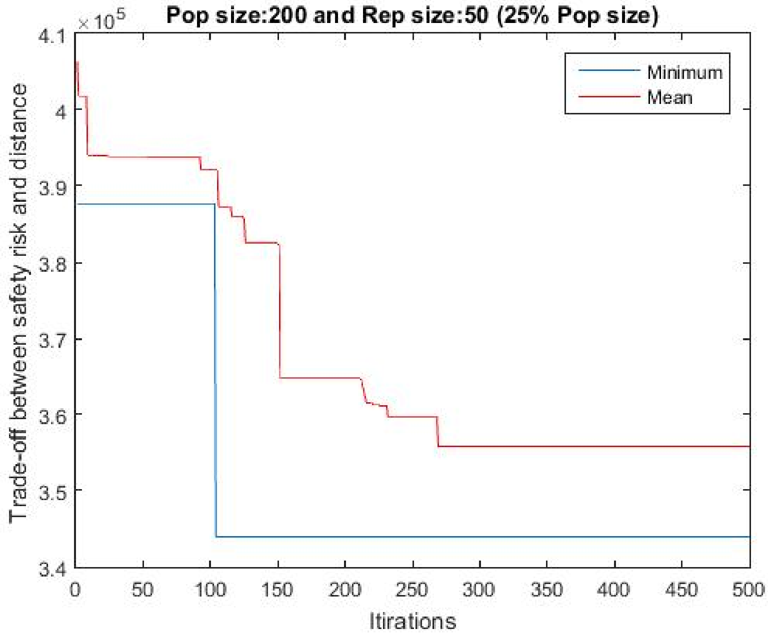

Pop size:150 and Rep size:53 (35% Pop size)
×10^5
Minimum
Mean
Trade-off between safety risk and distance
Itirations
6.5
6
5.5
5
4.5
4
3.5
3
0
50
100
150
200
250
300
350
400
450
500

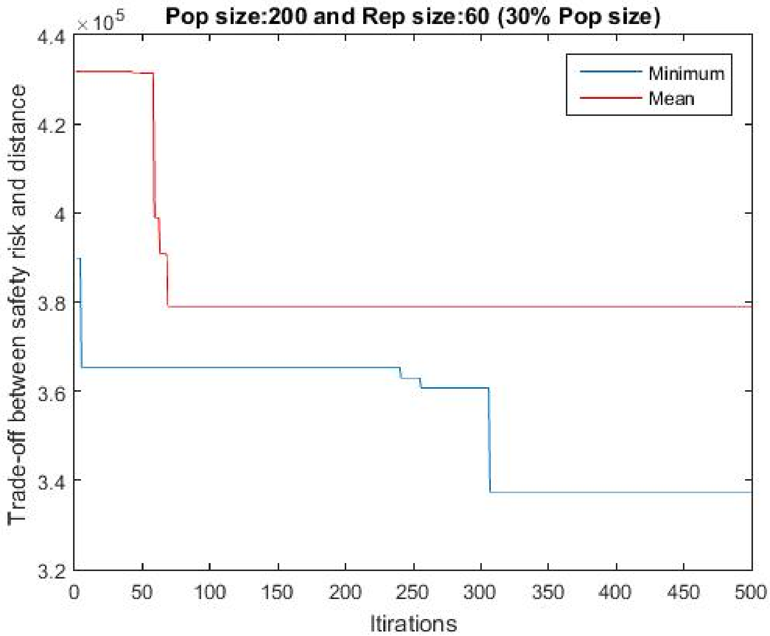

Pop size:150 and Rep size:60 (40% Pop size)
×10^5
Minimum
Mean
Trade-off between safety risk and distance
Itirations
5.2
5
4.8
4.6
4.4
4.2
4
3.8
3.6
3.4
3.2
0
50
100
150
200
250
300
350
400
450
500

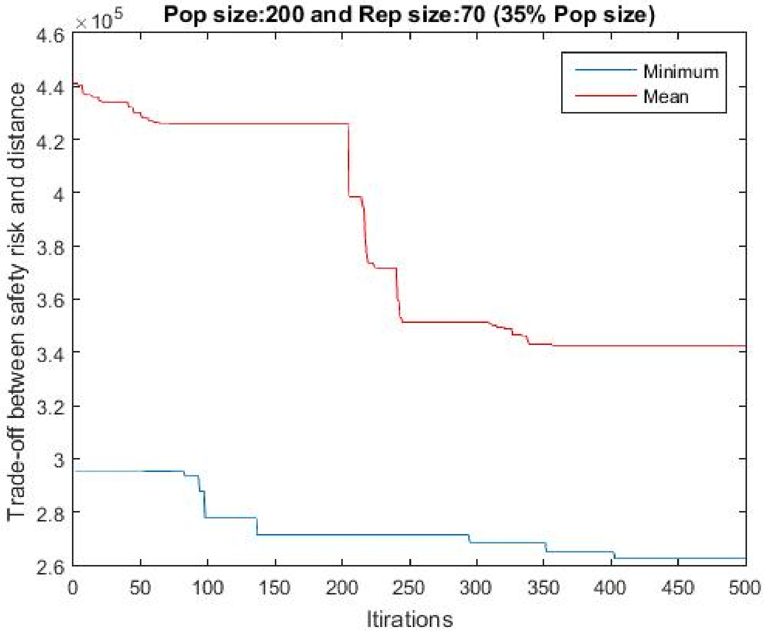

Pop size:150 and Rep size:68 (45% Pop size)
×10^5
Trade-off between safety risk and distance
Itirations
Minimum
Mean
5.5
5
4.5
4
3.5
3
2.5
0
50
100
150
200
250
300
350
400
450
500

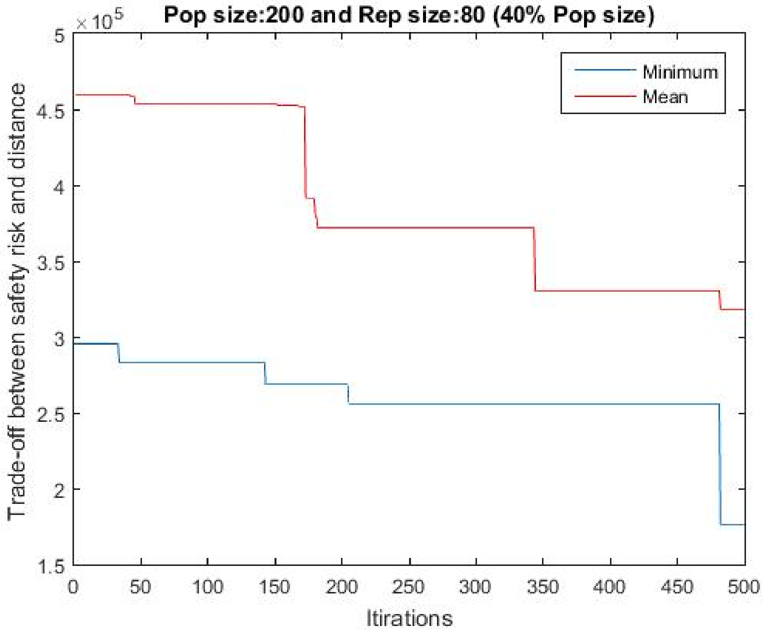

Pop size:150 and Rep size:75 (50% Pop size)
×10^5
Trade-off between safety risk and distance
Itirations
Minimum
Mean
5.5
5
4.5
4
3.5
3
2.5
0
50
100
150
200
250
300
350
400
450
500

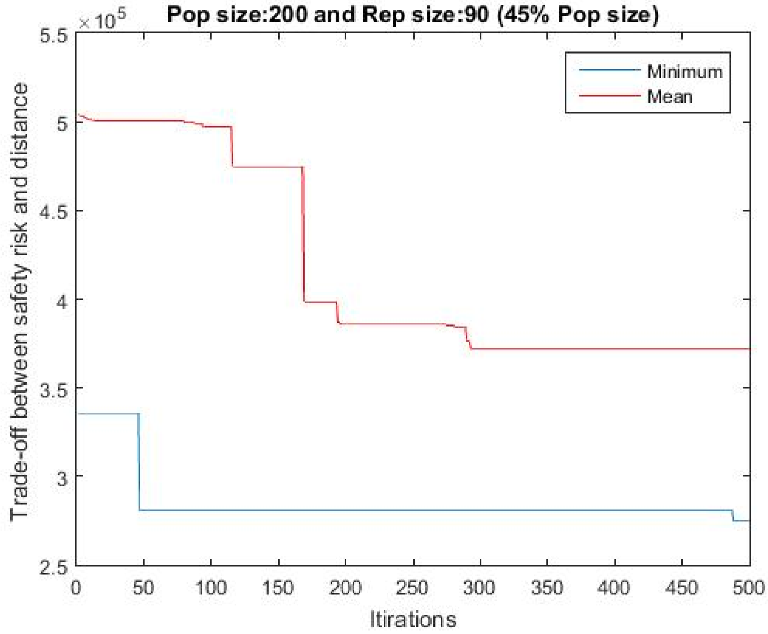
4. Mean and Minimum Values for Population Size 200 and Repository Size 25%, 30%, 35%, 40%, 45% and 50%

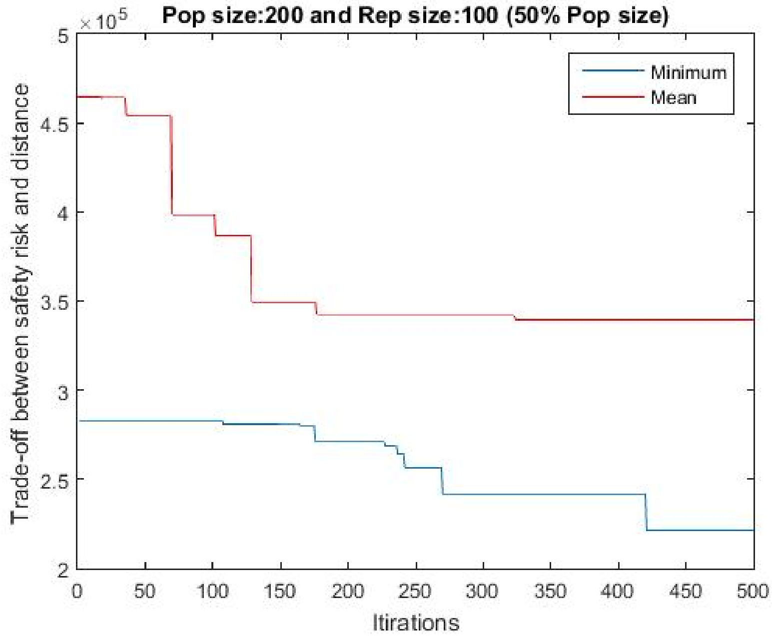




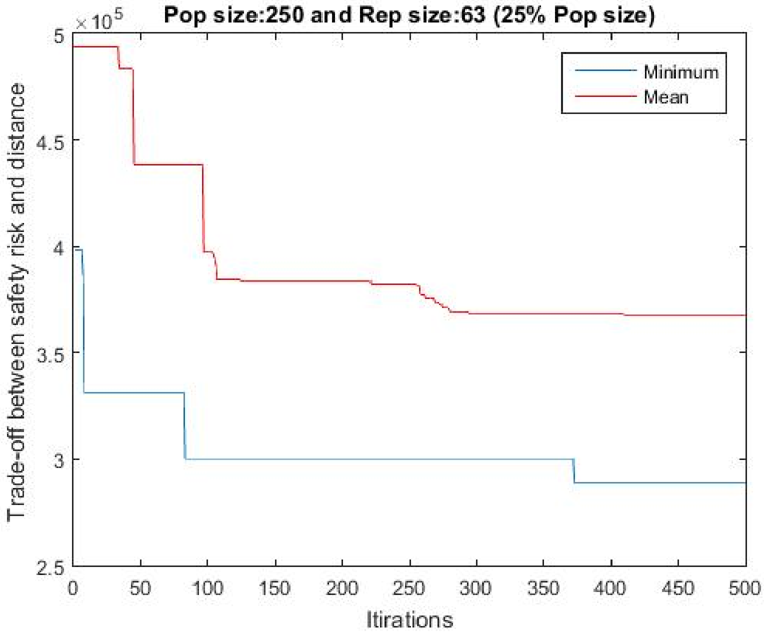

Pop size:200 and Rep size:70 (35% Pop size)
×10^5
Minimum
Mean
Trade-off between safety risk and distance
Itirations
4.6
4.4
4.2
4
3.8
3.6
3.4
3.2
3
2.8
2.6
0
50
100
150
200
250
300
350
400
450
500

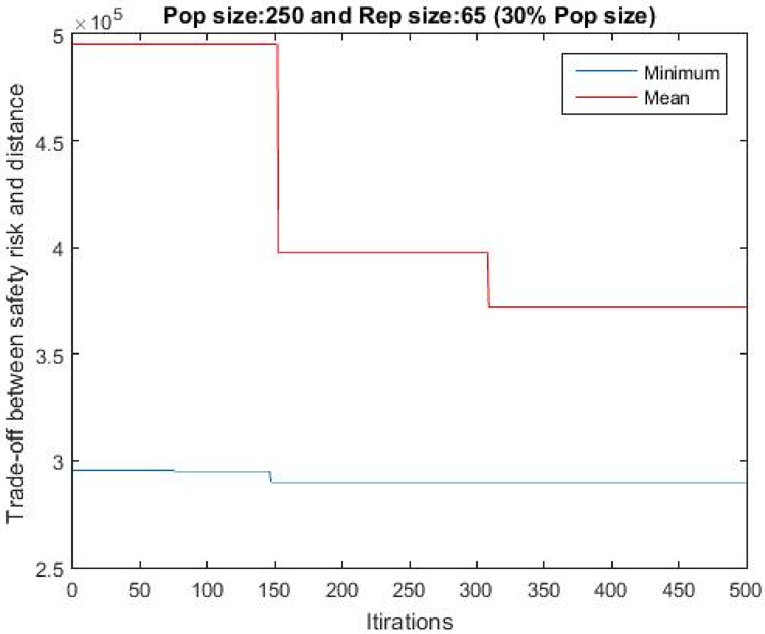

Pop size:200 and Rep size:80 (40% Pop size)
×10^5
Minimum
Mean
Trade-off between safety risk and distance
Itirations
5
4.5
4
3.5
3
2.5
2
1.5
0
50
100
150
200
250
300
350
400
450
500

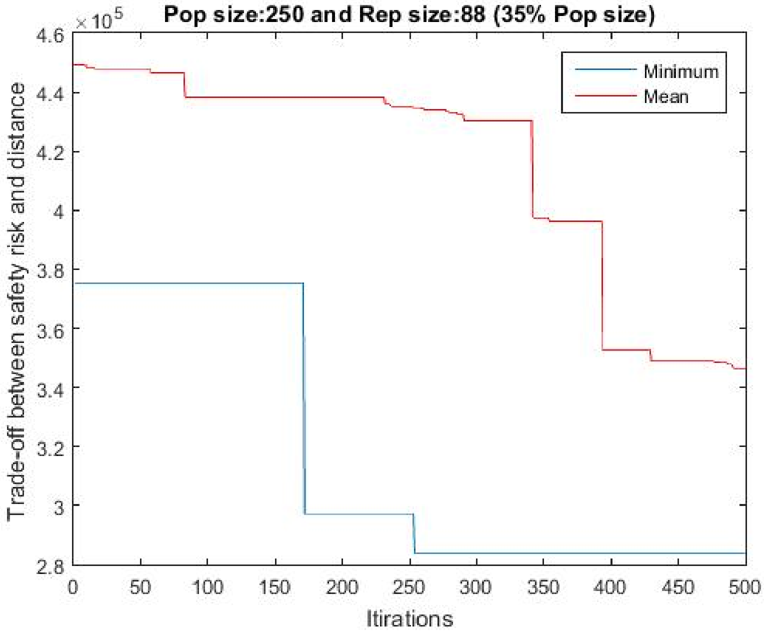

Pop size:200 and Rep size:90 (45% Pop size)
×10^5
Minimum
Mean
Trade-off between safety risk and distance
Itirations


Pop size:200 and Rep size:100 (50% Pop size)
×10^5
Minimum
Mean
Trade-off between safety risk and distance
Itirations

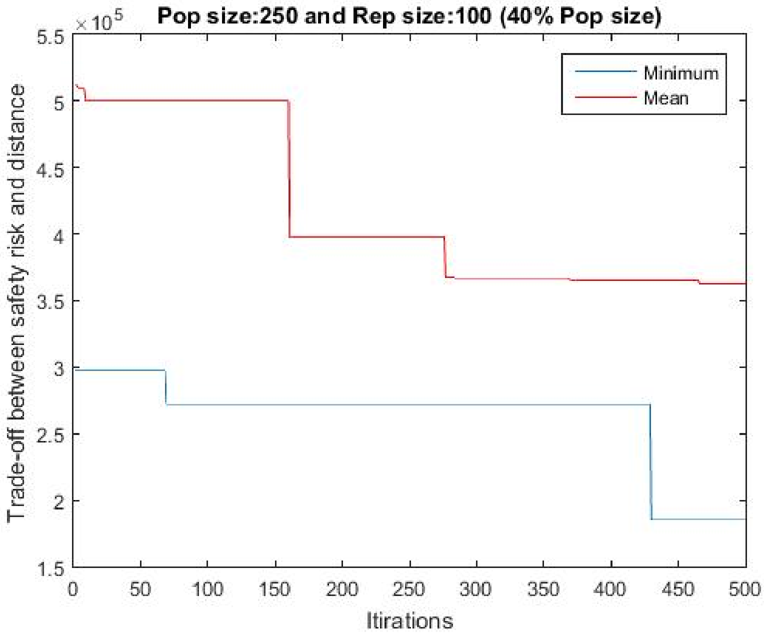
5. Mean and Minimum Values for Population Size 250 and Repository Size 25%, 30%, 35%, 40%, 45% and 50%



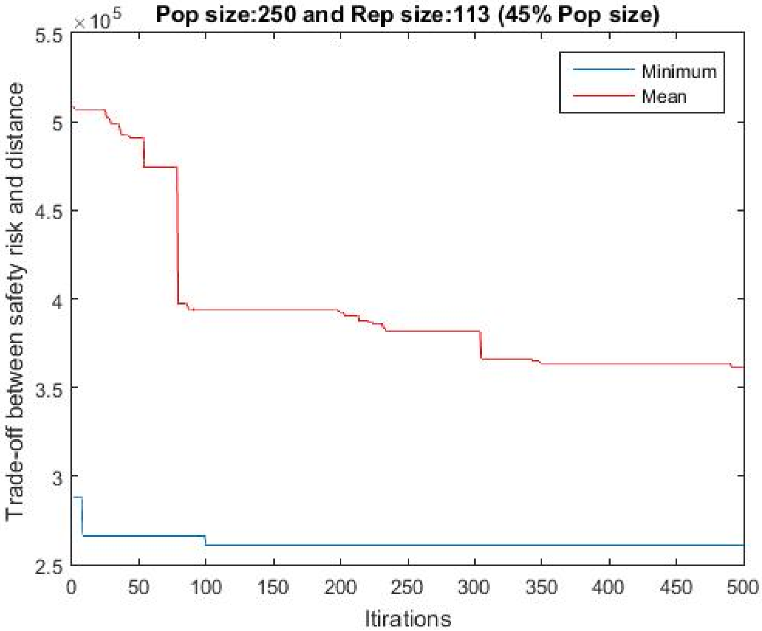


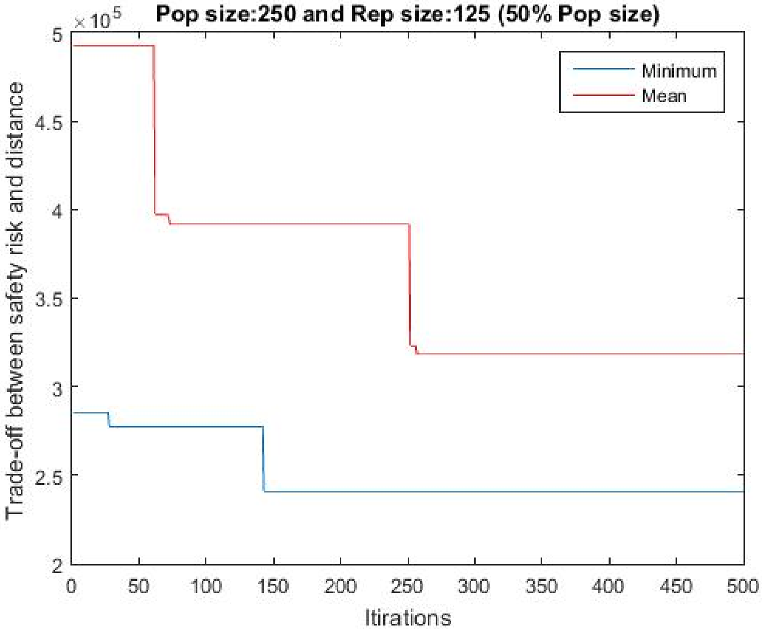


Pop size:250 and Rep size:88 (35% Pop size)
×10^5
4.6
4.4
4.2
4
3.8
3.6
3.4
3.2
3
2.8
Trade-off between safety risk and distance
0
50
100
150
200
250
300
350
400
450
500
Itirations
Minimum
Mean



Pop size:250 and Rep size:100 (40% Pop size)
×10^5
5.5
5
4.5
4
3.5
3
2.5
2
1.5
Trade-off between safety risk and distance
0
50
100
150
200
250
300
350
400
450
500
Itirations
Minimum
Mean


Pop size:250 and Rep size:113 (45% Pop size)
×10^5
Minimum
Mean
Trade-off between safety risk and distance
Itirations
5.5
5
4.5
4
3.5
3
2.5
0
50
100
150
200
250
300
350
400
450
500


Pop size:250 and Rep size:125 (50% Pop size)
×10^5
Minimum
Mean
Trade-off between safety risk and distance
Itirations
5
4.5
4
3.5
3
2.5
2
0
50
100
150
200
250
300
350
400
450
500

APPENDIX 2: QUESTIONAIRE

1. Personal Info

1. Personal Info						
Profession	Civil engineering	Architect	Technical personnel	Occupational health and safety officer		
Position	Project Manager	Construction manager	Senior engineer	Site engineer with 15 years experience	Site engineer with 8 years experience	Other

2. Experts assessments related to the possibility of the safety risks due to the strucks of tower crane loads on the temporary facilities

Fatal & Injuries incidents Related *Struck by tower crane loads* with	**RS (Risk severity)**				
	Very low (VL)	Low (L)	Medium (M)	High (H)	Vary high (VH)
Welding workshop					
Contractor office					
Rest room					
parking					
wc					
Fuel stock					
Tool stock					
Generator					

3. Experts assessments related to the possibility of the safety risks due to the load falls from the tower crane on the temporary facilities

Fatal & Injuries incidents Related *the load falls from the tower crane on*	**RS (Risk severity)**				
	Very low (VL)	Low (L)	Medium (M)	High (H)	Vary high (VH)
Welding workshop					
Contractor office					
Rest room					
parking					
wc					
Fuel stock					
Tool stock					
Generator					

4. Experts assessments related to the possibility of the safety risks due to the crane collapses on the temporary facilities facilities

Fatal & Injuries incidents Related *tower crane collapses*	**RS (Risk severity)**				
	Very low (VL)	Low (L)	Medium (M)	High (H)	Vary high (VH)
Welding workshop					
Contractor office					
Rest room					
parking					
wc					
Fuel stock					
Tool stock					
Generator					

5. Proximity weight among Facilities

Proximity weight among Facilities	Evaluation Criteria: Absolutely necessary (A) Especially important (E) Important (I) Ordinary closeness(O) Unimportant (U) Undesirable(X)							
	Welding workshop	Contractor office	Rest room	Parking	WC	Fuel stock	Tool stock	Generator
Welding workshop								
Contractor office								
Rest room								
Parking								
WC								
Fuel stock								
Tool stock								
Generator								