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A MATHEMATICAL MODEL FOR SELECTING THE PROJECT RISK RESPONSES IN CONSTRUCTION PROJECTS

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ABSTRACT

Risks are natural and inherent characteristics of major projects. Risks are usually considered independently in analysis of risk responses. However, most risks are dependent on each other and independent risks are rare in the real world. This paper proposes a model for proper risk response selection from the responses portfolio with the purpose of optimization of defined criteria for projects. This research has taken into account the relationships between risk responses; especially the relationships between risks, which have been rarely considered in previous works. It must be pointed out that not considering or superficial evaluation of the interactions between risks and risk responses reduces the expected desirability and increases project execution costs. This model is capable of optimization of different criteria in the objective function based on the proposed projects. Multi-objective Harmony Search (MOHS) and Non-dominated Sorting Genetic Algorithm II (NSGA-II) are used to solve this model and the numerical results obtained are analyzed. Finally, it was observed that ranges of objective functions in MOHS are better than those in NSGA-II.

Keywords: risk response; project risk management; risk interactions; risk interdependence; NSGA-II algorithm; MOHS algorithm.

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1. INTRODUCTION

Following the 2008 crisis, risk forecasting has emerged as a key public concern [1]. Naturally, Maximization of value is the ultimate goal for any business organisation. Return on investment is the main driver of this value. However, high returns can not be achieved

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without risk, hence, the positive relation between the two [2]. Therefore, Project Risk Management (PRM) is necessary for ensuring project success [3]. PRM generally consists of three phases [4]: risk identification, risk analysis and risk response. Risk analysis refers to identification of documentation of the related risks. Risk assessment deals with the examination of identified risks, correction of risk descriptions and estimation of the effects and the corresponding possibilities. Risk response is associated with identification, assessment, selection and execution of necessary measures in order to decrease the likelihood of risks and their negative effects. Risks response plays a major role in the reduction of negative effects [5]. Appropriate risk response strategies ought to be able to carry out risk identification and analysis in execution of a project [6]. Therefore, risk response strategy is an important issue in PRM [7]. However, little work has been done on risk response strategies, which are an important part of PRM. In the analysis of risk responses in order to select the response strategy, risks are considered independent [8]. However, risks are usually dependent and interact with one another [9]. In fact, the interactions between risks must be considered as an important part of risk analysis [10]. Interactions, which are the defining elements of project complexity [11], make projects more complicated [12]. Therefore, if risk interactions are well analyzed, the decision-making process for responding to risks will be more effective [13]. In addition to that, multiple criteria decision making methods have been applied in many risk management contexts [14].

The objective of this work is introduction of an optimal mathematical model considering the relationships between risk responses; especially the interactions between risks in order to choose the appropriate response strategy. This model can help project manager select response strategies by maximizing the effects of execution of risk response strategies (by considering the cost, quality and the time of each strategy). In addition, the interaction between risks in decision-making is studied. It is understandable that interactions such as those between risk responses are effective on determination of risk response strategies. Furthermore, paying more attention to the interactions between risks can increase the expected benefit and lower execution costs. The interactions between risks and their responses have hardly been studied in previous works although these relationships are undeniable in the real world. Thus, in order to manage an oil and gas project the risks of which are dependent, it is important to form different risk dimensions and make a model of risk interactions in the PRM process. In order to express the real complexities of a project, risk interactions must be modeled using a network structure rather than an old list or tree structure. In this work, a structure has been proposed for modelling and analysis of risk network behavior to support project management decision-making. To analyze and assess the interactions between risks, Risk Structure Matrix Methods consisting of methods such as Design Structure Matrix (DSM) and Analytic Hierarchy Process (AHP) are used. It must be acknowledged that the simulation technique is used for analysis of the promoted effects and reassessed risks [15]. The reason for these calculations is supporting the decision makers in planning the corresponding risk response measures using a structured and repeatable approach. The second part of this paper reviews the prior art in the area of risk response. In the third part, the problem has been analyzed considering the relations between risks and risk responses, which have not yet been dealt with in the literature. The preparation of a risk structure matrix is explained in the fourth section and the fifth section presents the mathematical model. The results of calculations of the proposed algorithm are explained in details in the next section and conclusions have been made in the final part.

2. LITERATURE REVIEW

Project execution is always accompanied by risks and the studies on project risks and risk interdependence have always been the topics of concern in academia and practice. Project managers will be as much interested and as rational as security investors when striving to reduce their own specific risk through various project risk management and risk diversification strategies [16]. Some studies on the project risk interdependence from qualitative perspectives. Adner [17] points out that the success of a company's growth strategy hinges on the assessment of the ecosystem's risks of the company. The ecosystem is characterized by three fundamental types of risks: initiative risks, interdependence risks and integration risks. Manoj et al. [18] show how the supply disruptions at a US port can affect the availability of material for a certain product, thus determining the need to define a risk mitigation plan. Dikmen et al. [19] have proposed training based approach for risk management and applied this tool to an ongoing construction and project because they believed that risk management was a task, which had to be performed during the project life cycle. The case study proved that such tool could be used for storage and updating of the data related to the project and ultimately the evaluations following the project. The major weak point of this tool is identification of risks and their ranking trend as well as the reluctance of the employees for feeding the information concerning reasons for risks. Kwan and Leung [13] have proposed methods to estimate risks by taking into account of risk dependence effects, and risk response strategies. Focusing on risk dependences should also be developed. López and Salmeron [20] have carried out some research on identification of software project risks affecting the performance of such projects. They have then used a functional approach in the assessment of the risks identified and finally presented appropriate responses for management of these risks. Fatah et al. [21] propose a new risk-preference model for ranking pairs of normalized lotteries, random variables, each represents a risk factor obtained by converting the outcomes of the lottery into its mean multiplied by a risk factor. Taaffe et al. [22] investigate how a selective newsvendor can integrate risk into its demand selection and ordering policy. They have the added complexity of market selection, which can result in different procurement policies.

It can be seen that studies pertinent to project risk response strategy selection have aroused attention by some scholars from different perspectives. A summary of related literature on project risk response strategy selection is shown in Table 1. The approaches involved in the existing studies can be mainly classified into four categories [23]: the zonal based approach, the trade-off approach, the Work Breakdown Structure (WBS) based approach and the optimization model approach. In the following, the brief descriptions and comments on these approaches will be given.

In the zonal based approach, two selected criteria with respect to risks are mapped to the horizontal axis and vertical axis, respectively. The two selected criteria are the weighted probability of immediate project risk and that of external project risk [24], the extent to which risks are controllable and degree to which risks are specific to the project [5]. According to different values of the two criteria, a two axis graph composed of multiple zones is formed. Different strategies are placed in their corresponding zones. Thus, appropriate strategies can be selected according to the zones in which the coordinates constituted of the two criterion values are located. The two dimensional zonal based approach can be considered as an approximate tool for selecting risk response strategies [25]. It has a limitation that only two criteria can be considered.

In the trade-off approach, in order to obtain candidate risk response strategies, trade-offs are made considering objective requirements of the oil and gas project and managers' subjective preferences between criteria associated with risk such as cost, probability of success, percentage of work losses, duration, quality, and so on. Then the desirable strategies can be selected among the candidate ones according to efficient frontier rule [26, 27], Pareto optimal solution [28] and decision maker's preference [29]. However, these approaches either consider only two factors or make trade-offs based on qualitative analysis.

The WBS based approach is regarded as the one based on risk management and the project management process. It relates risk response strategy selection to work activities based on project WBS analysis. When the analyzed activity is the actual one, risks are identified and strategies can be formulated directly associated with that activity [30] or selected among candidate ones by an index of scope expected deviation [31]. When the analyzed activity is the prototype one, a set of rules can be developed to show how risk analysis for the prototype activity is converted into that for the actual one, and then a set of strategies may be generated for all the activities represented by the prototype activity [32]. However, it is unknown whether the strategies obtained are optimal solutions to the strategy selection problem.

The optimization model approach constructs a mathematical model to solve the risk response strategy selection problem. Generally, in the model, the objective function is to minimize the cost of implementing strategies, and the constraints include combinations of the strategies, the acceptable level of the loss of risks, the budget of implementing the strategies [7, 8, 33, 34] and so on.

The above approaches have made significant contribution to risk response strategy selection from different perspectives. According to studies, a limited research is accomplished on the relationship between risks and their responses and particularly the interactions between risks [35]. However, there are some limitations in the existing approaches. For example, only two criteria can be considered in the zonal based and trade-off approaches, and there is lack of more precise mathematical solution to the problem in the trade-off and WBS based approaches. In addition, all the approaches, except the WBS based approach, can just be applied to small scale projects, in which risk analysis is easily made to the whole project directly without the need for presenting the project's discrete work activities.

Therefore, it is necessary to develop a new approach to project risk response strategy selection. In recent years, the approach based on Design Structure Matrix (DSM) [42], which represents relations and dependences among objects, has been developed [15, 43, 44]. The core of the approach is to capture and represent project risk interdependences by building up matrices. The approach mainly includes two steps. First, a binary matrix representing the existence of potential interdependence between each pair of risks is built. Secondly, the binary matrix is transformed into a numerical one to assess the strength of risk interdependence, in which the Analytic Hierarchy Process (AHP) [45] is used. Fang et al. [44] proposed a framework for risk response strategy selection considering that the risk interactions and the DSM method mentioned above are applied to identify the risk interactions. In their work, however, the effect of the risk interactions on the project risk response decisions is not analyzed, which produces a space guiding us to make deep thinking and conduct a further study in this aspect. In this study, we will try to fill this gap by proposing an optimization model for selecting risk response strategies and further analyze the effects of the risk interdependence on decisions about project risk response. It should be noted that Soofifard and Khakzar Bafruei [40] proposed a linear integer programming optimization model was used in this work to solve a problem when failing to acknowledge risk interdependencies in order to choose the most appropriate risk responses for the project risks.

Table 1: Literature on project risk response strategy selection

Authors	**Focus of analysis**	**Approaches**
Flanagan and Norman [36]	The likelihood of occurrence and severity of the risks	The zonal based approach
Elkjaer and Felding [37]	The degrees of influence and predictability of the risks	
Datta and Mukherjee [24]	The weighted probability of immediate project risk and that of external project risk	
Miller and Lessard [5]	The extent to which risks are controllable and degree to which risks are specific to the project	
Piney [38]	The acceptability of impact and probability of risks	
Klein [29]	Uncertainties in project duration, cost and quality	
Chapman and Ward [39]	The expected costs of risk response strategies and uncertainty factors of the expected costs	The trade-off approach
Pipattanapiwong and Watanabe [27]	The expected cost of risk after applying the risk response strategy and degree of risk to access the risk response strategy	
Kujawski [26]	The probability of success for a given total project cost and the total project cost for a given probability of success	
Haimes [28]	The cost of risk response strategy and percentage of work losses associated with the risk response strategy	
Chapman [30]	Work activities and risks and risk response activities associated with the work activities	The WBS based approach
Klein et al. [32]	A variation on Chapman based on the analysis of a prototype activity	
Seyedhoseini et al. [31]	Selecting a set of response actions, which minimize the undesirable deviation from achieving the project scope	
Ben-David and Raz [7]	Project work contents, risk events, and risk reduction actions and their effects	
Ben-David et al. [33]	Interactions among work packages with respect to risks and risk abatement efforts	
Kayis et al. [34]	The available mitigation budget and strategic objectives of the project	The optimization model approach
Fan et al. [8]	The risk handling strategy and relevant project characteristics	
Zhang and Fan [23]	Selecting a set of response actions, which maximize the estimated risk response effects	
Soofifard and Khakzar [40]	Selecting a set of response actions, which optimize relationship between responses with regards to the interactions between responses in certain areas	
Soofifard and Khakzar [41]	Selecting a set of response actions, which optimize relationship between responses with regards to the interactions between responses in uncertain areas	

3. STATEMENT OF THE PROBLEM

Risk identification, usually the first step for project risk analysis, is the process of determining risk events, which could affect project objectives negatively or positively [46]. The risk interdependence is defined as the existence of a possible precedence relationship between two risks R_i and R_j [43, 47]. The analysis of the risk interdependence is performed on a direct link, which means that there is no intermediary risk between the two risks [43]. In addition, the effect of the risk interdependence refers to an effect of one risk on the other risk arising from the direct interdependence. Specifically, there are two kinds of effects of risk interdependences considered in the paper, which are unfavorable and favorable effects. The unfavorable effects will increase the expected loss by increasing the probability and/or the impact of the other risk, while the favorable effects will reduce the expected loss by lowering the probability and/or the impact of the other risk. It should be noted that in this paper, interactions between risks analyzed with risk structure matrix (RSM) will be explained.

According to the literature review, a mathematical model is developed here for selection of project risk responses. Different risks are considered for the oil and gas project activities, and different responses are selected for each risk. In addition, risk responses have not been considered individually, but are correlated. The selection of related responses can affect their influence on the project objectives. These effects can appear as positive or negative synergisms. If the specific numbers of related response sets are selected, the synergism (positive or negative) results will enhance the individual effect of each response. Different assessment criteria are considered in the objective function, which attempts to select responses for maximizing the amount of effects resulting from these criteria. If one criterion is considered, the problem will turn into a single objective mathematical model.

In this study, using the optimization model approach for selection of risk responses, first, a conceptual model for evaluation and selection of project risk responses is proposed, which clearly relates WBS, risk events, risk reduction actions, and their effects. It is necessary to consider the WBS as the relationship basis in order to establish a relationship between the risk response selection models and general project management system. The relationship is such that if a specific number of responses are selected, a positive or negative synergism will be activated between the responses. In other words, the WBS is an important basis in integration of a comprehensive project management system with other subsystems such as risk management.

In the proposed model, it is attempted to select a set of responses such that the objective function is optimized in addition to meeting the system constraints (budget, technical dependences of responses, etc.). The objective is maximizing the expected desirable effects resulting from the risk responses ($i = 1,2,\ldots,m$) on a number of desirable project objective criteria ($l = 1,2,...,L$). The working elements are the same as the components of WBS and are represented as $k = 1,2,\ldots,K$, and the risks are represented by $j = 1,2,\ldots,n$. Risk responses interact with each other and are assumed to be independent. Risk events may negatively or positively affect one or more work activities. The relationship between risk events and responses and their effects on the project objectives are shown in Fig. 1 [41].

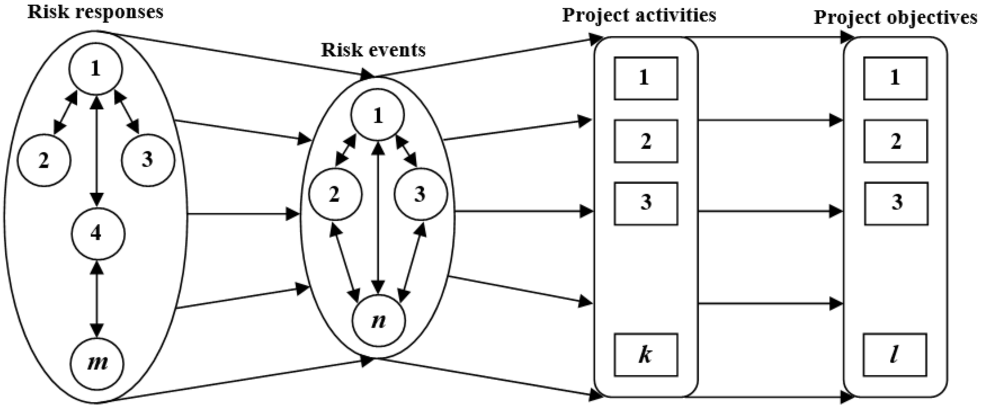

Figure 1. Proposed framework for problem

3.1 Risk structure matrix (RSM)

The Design Structure Matrix (DSM) represents relations and dependencies among objects. The same objects are both in the rows and columns of the square matrix. The DSM was introduced by Steward [42] with tasks and was initially used basically for planning issues [48]. In order to build the RSM, the interactions between project risks have to be identified. The iterative procedure used is notably addressed in ongoing publications. Classically, the DSM is re-ordered in a way, which permits to show first level blocks, using the well-established partitioning process [48].

In order to do so, firstly an AHP based evaluation is used to transform the RSM into a numerical matrix, which is to catch the strength of local interactions. Five steps are necessary to carry out our methodology. Fig. 2 shows this process with an example for risk R_4 [47]:

Step 1: Decomposing individual sub-problems: The presence of a1 in the binary RSM expresses the existence of a possible precedence relationship between risks R_i and R_j. $RSM_{ij}=1$ implies two possible ways to address the situation. If there is a cause effect relationship between R_i and R_j, then it is equivalent to consider R_i as a cause of R_j or R_j as an effect of R_i. Similarly, as in Chen and Lin [49] for design tasks, these visions were combined. Two stages must thus be performed. For each R_i, the risks are isolated and related with R_i in columns (possible effects) and rows (possible causes). This permits a sanity check because each relationship has to be expressed two times. This identification enables generation of the Binary Cause or Effect Vectors, which are relative to one risk R_i (respectively, $BCV|R_i$ and $BEV|R_i$).

Step 2: Evaluating the strength of interactions: Two matrices are built up regarding the risk R_i based on the two previously isolated sets of risks (in rows and columns), which constitute the set of alternatives. These are called Cause or Effect Comparison matrices and are both realted to one risk R_i ($CCM|R_i$ and $ECM|R_i$). Given the AHP numerous applications in the field of project management and project risk management, the use of the AHP based principle of pair wise comparisons is claimed to assess project risk interactions (as defined in this article). The Analytic Hierarchy Process was developed by Saaty [45, 50]. It is a multi-criteria decision-making method. It permits the relative assessment and prioritization of alternatives. The AHP is based on the use of pair wise comparisons, which lead to the elaboration of a ratio scale.

Step 3: Consolidating the results: Eigenvectors of each matrix ECM|R_i and CCM|R_i are now to be calculated. This enables finding the principal eigenvectors, relative to the maximal eigenvalue. These are called the Numerical Cause or Effect Vectors and are relative to one risk R_i (NCV_i and NEV_i). Consistency of the results should be tested using the AHP consistency index.

Step 4: Aggregating the results: For each risk R_i, Numerical Cause or Effect vectors are, respectively, aggregated into Numerical Cause/Effect Matrices (NCM and NEM). The ith row of NEM corresponds to the eigenvector of CCM|R_i, which is associated to its maximum eigenvalue. The jth column of NCM corresponds to the eigenvector of ECM|R_j, which is associated to its maximum eigenvalue.

Step 5: Compiling the results: The two previous matrices are aggregated into a single Risk Numerical Matrix (RNM), the values of which assess the relative strength of local interactions. The RNM is defined by a geometrical weighting operation (based on the possible assumption that both estimations can be considered as equivalent). The geometrical mean was chosen instead of the arithmetic mean because it tends to favor balanced values (between the two assessments).

$$\begin{gathered} RNM(i,j) = \sqrt{NCM(i,j) \times NEM(i,j)} \\ \forall (i,j), 0 \leq RNM(i,j) \leq 1 \end{gathered} \tag{1}$$

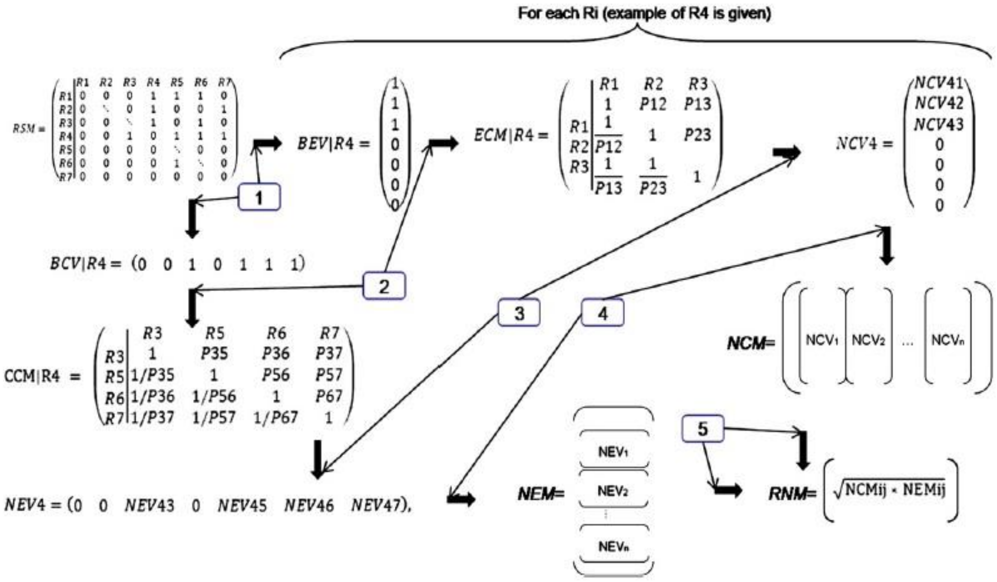

Figure 2. Description of the transformation process from RSM to RNM

3.2 Modeling

The mathematical method developed in this paper intends to select proper responses for project risks. It is a multi-objective and Binary Integer Programming (BIP). The objective is maximizing the desirable effects of criteria in the projects. Sets, parameters and variables are defined as follows:

Sets:

$A = \{A_1,A_2,\ldots,A_m\}$	Risk responses	$i = 1,2,\ldots,m$
$B = \{B_1,B_2,\ldots,B_n\}$	Risks	$j = 1,2,\ldots,n$
$W = \{W_1,W_2,\ldots,W_K\}$	Activities	$k = 1,2,\ldots,K$
$C = \{C_1,C_2,\ldots,C_L\}$	Assessment criteria (project objectives)	$l = 1,2,\ldots,L$
B^k	Risks for activity k	$k = 1,2,\ldots,K$
St_j^k	The set of responses related to risk j for activity k. Its selection and implementation cause synergism of their effect on the jth risk.	$j = 1,2,\ldots,n$ $k = 1,2,\ldots,K$

Parameters:

B	Maximum available budget for selection of risk responses
$\overleftrightarrow{M}$	The set of all pairs of strategies, which exclude each other
$\overline{M}$	The set of all pairs of strategies, which cooperate with each other
c_i^k	Cost required for implementation of the ith risk response for activity k
s_j^k	Variation in time of activity k if risk j occurs
$\tilde{s}_{ij}^k$	Improvement in the time of activity k if the ith risk response is implemented to control the jth risk
$\widetilde{sa}_j^k$	Variation in time of activity k resulting from the synergism of risk responses related to the jth risk
ε^k	Maximum allowable delay for activity k
q_j^k	The quality of activity k affected by risk j
$\tilde{q}_{ij}^k$	The quality of activity k changed if the ith risk response is implemented to control the jth risk
$\widetilde{qa}_j^k$	The quality of activity k changed resulting from the synergism of implementation of risk responses related to the jth risk
δ^k	Maximum allowable quality reduction for activity k
Atr_{ij}^{lk}	Effect of the ith risk response effective on the jth risk for the kth activity on the lth criterion
g_j^{lk}	Synergism resulting from the risk responses related to the jth risk for the kth activity on the lth criterion
m_j^k	Minimum risk responses selected for synergism for the jth risk and the kth activity
M_j^k	Maximum risk responses selected for synergism for the jth risk and the kth activity
RNM_{fj}	Effect of the fth risk on jth risk within risk structure matrix

Variables:

x_{ij}^k	If the ith risk response is selected for the jth risk in the kth activity, it is 1, otherwise zero

LM_j^k If synergism for the jth in the kth activity risk occurs, it is 1, otherwise zero

Model:

Considering the parameters and variables of the problem, the Binary Integer Programming (BLP) model of this work is presented as follows:

$$\text{Max } z = \sum_{k=1}^{K} \sum_{j \in B^k} \left(\sum_{i \in St_j^k} Atr_{ij}^{lk} x_{ij}^k + \sum_{f \in B^k} RNM_{fj} \sum_{o \in St_f^k} Atr_{of}^{lk}\, x_{of}^k \right) + \sum_{k=1}^{K} \sum_{j \in B^k} g_j^{lk} LM_j^k \qquad (2)$$
$$l = 1,2,\dots,L$$

s.t.

$$\sum_{k} \sum_{i \in St_j^k} c_i^k \max_{j} x_{ij}^k \le B \qquad (3)$$

$$\sum_{j \in B^k} s_j^k - \left(\sum_{j \in B^k} \left[\sum_{i \in St_j^k} \tilde{s}_{ij}^k x_{ij}^k + \sum_{f \in B^k} RNM_{fj} \sum_{o \in St_f^k} \tilde{s}_{of}^k\, x_{of}^k + \widetilde{sa}_j^k LM_j^k \right] \right) \le \varepsilon^k \qquad (4)$$
$$k = 1,2,\dots,K$$

$$\sum_{j \in B^k} q_j^k - \left(\sum_{j \in B^k} \left[\sum_{i \in St_j^k} \tilde{q}_{ij}^k\, x_{ij}^k + \sum_{f \in B^k} RNM_{fj} \sum_{o \in St_f^k} \tilde{q}_{of}^k\, x_{of}^k + \widetilde{qa}_j^k LM_j^k \right] \right) \le \delta^k \qquad (5)$$
$$k = 1,2,\dots,K$$

$$\sum_{i \in St_j^k} x_{ij}^k - m_j^k + 1 \le M \times LM_j^{km} \le \sum_{i \in St_j^k} x_{ij}^k - m_j^k + M \qquad (6)$$
$$k = 1,2,\dots,K \qquad j = 1,2,\dots,n$$

$$M_j^k - \sum_{i \in St_j^k} x_{ij}^k + 1 \le M \times LM_j^{kM} \le M_j^k - \sum_{i \in St_j^k} x_{ij}^k + M \qquad (7)$$
$$k = 1,2,\dots,K \qquad j = 1,2,\dots,n$$

$$LM_j^{kM} \times LM_j^{km} = LM_j^k \qquad (8)$$
$$k = 1,2,\dots,K \qquad j = 1,2,\dots,n$$

$$x_{ij}^k + x_{i'j'}^{k'} \le 1 \qquad (9)$$
$$\left(A_i, A_{i'}\right) \epsilon\, \overleftrightarrow{M} \qquad i,i' = 1,2,\dots,m \qquad j,j' = 1,2,\dots,n \qquad k,k' = 1,2,\dots,K$$

$$x_{ij}^k + x_{i'j'}^{k'} = 1 \qquad (10)$$
$$\left(A_i, A_{i'}\right) \epsilon\, \overleftrightarrow{M} \qquad i,i' = 1,2,\dots,m \qquad j,j' = 1,2,\dots,n \qquad k,k' = 1,2,\dots,K$$

$$x_{ij}^k - x_{i'j'}^{k'} \le 0 \qquad (11)$$
$$\left(A_i, A_{i'}\right) \epsilon\, \overleftrightarrow{M} \qquad i,i' = 1,2,\dots,m \qquad j,j' = 1,2,\dots,n \qquad k,k' = 1,2,\dots,K$$

$$x_{ij}^k, x_{i'j'}^{k'}, LM_j^k, LM_j^{km}, LM_j^{kM} \epsilon \{0,1\} \qquad (12)$$
$$i,i' = 1,2,\dots,m \qquad j,j' = 1,2,\dots,n \qquad k,k' = 1,2,\dots,K$$

In this model, the objective function aims at optimizing the quantity obtained from each assessment criterion including the sum of effects resulting from the selection of each risk response in that criterion as well as the sum of effects of synergism for each risk.

Constraint 1 states that the cost of implementation of risk responses must be less than the allocated budget. According to constraint 2, risk responses must be selected such that the difference in improvement in time of the kth activity and the effect of risk on its time must be less than the expected value. Constraint 3 states that risk responses must be selected such that the difference in improvement in time of the kth activity and the effects of risk on quality of kth activity must be less than the expected value. According to constraints 4-6, if a known number of risk responses are selected for the corresponding risk, the resulting synergism will increase or decrease the effect of that risk. Constraint 4 implies that if the number of responses selected is greater than m_j^k, LM_j^{km} will be one, and otherwise zero. In addition, according to constraint 5, if the number of responses selected is less than M_j^k, LM_j^{kM} will be one, and otherwise zero. Constraint 6 states that if the number of responses selected is within the desirable range, synergism will be activated and LM_j^k will be equal to 1, and otherwise zero. Furthermore, M in constraints 4 and 5 is a very large number (Big M). Constraints 7-9 are known as balance constraints. Constraint 7 states that strategies A_i and $A_{i'}$ exclude each other. Constraint 8 ensures that one strategy must be selected in the case of strategy exclusion. Constraint 9 says that the selection of one strategy requires that another specific strategy be selected, too. Constraint 10 is also a binary mode indicator.

4. THE PROPOSED METHOD OF SOLVING THE PROBLEM

In this paper, meta-heuristic algorithms are used in order to solve the zero and one optimization model such that ε-constraint is used for problems of small dimensions and a comparison between Non-dominated Sorting Genetic Algorithm and Harmony Search has been done considering various performance indicators, which will be presented in the next section. In addition, since the problem is NP-Hard and cannot be solved by the exact ε-constraint method, the two algorithms mentioned will be used for problems of larger dimensions. First, these methods and algorithms are explained.

4.1 ε-constraint method

This method was first introduced by Haimes et al. [51]. This method is based on the conversion of a multi-objective optimization problem to a single objective one such that only one objective is optimized and the others are considered constraints. In fact, this is one of the known approaches for confronting multi-objective problems, which solves the problem by transferring all the objective functions, except for one, in each step to a constraint. The steps in ε-constraint method are as follows:

1. One of the objective functions is chosen as the major objective function.
2. The problem is solved each time by considering one of the objective functions, and the optimized values for each function are obtained.
3. The interval between two optimized values of the minor objective functions is divided to previously determined numbers and a table for is made $\varepsilon_2,\ldots,\varepsilon_n$.
4. The problem is solved each time with one of the major objective functions for each of the values of $\varepsilon_2,\ldots,\varepsilon_n$.

5. The Pareto responses found are reported.
   Equation (13) shows the format of the ε-constraint problem.

$$\begin{aligned} Min\, y = f(x) = f_1(x) \qquad\qquad & \epsilon\, x, y \\ f_2(\vec{x}) \leq\ \varepsilon_2 \\ \vdots \\ f_n(\vec{x}) \leq\ \varepsilon_n \end{aligned} \tag{13}$$

4.2 NSGA-II algorithm

One of the most efficient and well known multi-objective optimization algorithms is Non-dominated Sorting Genetic Algorithm II (NSGA-II), which was first introduced by Deb et al. [52]. This algorithm is one of the fastest and strongest optimization algorithms, which has less operational complexity compared with other methods. The algorithm gives the Pareto optimum points using the principle of non-dominance and calculation of crowding distance. It gives the designer the freedom to select the desired design from the optimized designs. Maintaining elitism and distribution have simultaneously been considered in NSGA-II. First, one population of children is formed using a population of parents, N being the size of both populations. These two populations are then combined to form a population with 2N members. The latter population is formed by categorized Non-dominated Sorting and ultimately a population of the best members up to N is obtained. Each categorized population is called a front.

4.3 MOHS algorithm

Harmony Search (HS) algorithm is one of the simplest and newest meta-heuristic methods, which starts searching for the problem solving space using s generation of solving vectors in the form of algorithm memory and moves toward optimized spaces, inspired by the simultaneous process of playing by the orchestra, based on possible approach. This method was first proposed by Geem [53]. In accordance with the logic of this meta-heuristic method, the attempt to achieve harmony in music is similar to finding the optimized solution in optimization problems. Harmony Search method is a promoting method like genetics. All the solving vectors available in the memory are used to produce improvised responses. Rapid convergence due to its appropriate structure is one of the advantages of this algorithm and entrapment in local tarps as a result of searching with little variations in the final repetitions of the algorithm is one of its disadvantages, which is overcome by the restart phase technique and variations in algorithm rules; especially in the final repetitions. Each musician plays some keys of his instrument to achieve better harmony in the orchestra. The objective of this process is reaching a situation in which there is complete harmony the output of which is a beautiful and standard melodious sound.

In HS algorithm, each solution is called a harmony and is shown as an N dimensional vector. A primary population is first formed randomly and stored in the harmony memory (HM). A new response vector is then formed randomly based on memory consideration rule, pitch adjustment rule and selection. Ultimately, the response vector created is compared with the worst response vector available in $\vec{X}_w$ memory. If the response vector created is better, it is substituted with the worst response vector and HM is thus updated. This process continues unit the stopping conditions are reached. Therefore, HS algorithm consists of the following three major steps: initialization, improvement of a new harmony and updating HM (for example, [54]). It must be pointed out the multi-objective harmony search algorithm (MOHS) is the developed form of HS and has been used in this work due to the type of research of interest.

5. COMPUTATIONAL RESULTS

To analyze the results of the proposed algorithm, it is first necessary to familiarize with specifications of sample problems, displaying the response, adjustment of parameters, and comparative indexes, which will be explained below.

5.1 Specifications of sample problems

Two methods have been proposed for solving a problem; exact and innovative methods. The problems have been used in this work to produce responses, as shown in Table 2. In addition, the parameters related to the problems have been randomly generated to evaluate the performance of the proposed algorithms and the uniform distribution function has been used to generate numbers. Furthermore, the range of generation of parameters for the proposed algorithms, based on the publications available in this regard is as follows (Table 3). Quality, cost and time have been considered as the criteria for evaluation of the functions. The amount of budget is 60% of the total cost. The minimum and maximum risks to create synergism are 2 and 6, respectively. Since the data are not accurate and exact and for the sake of simplicity, all risks are assumed to be effective on all activities and the all the responses affect all risks, but the effects are different.

Table 2: Specifications of solved problems

Problem	Number of activities	Number of risks	Number of risk response strategies
1	8	3	4
2	12	4	5
3	15	5	7
4	20	5	8
5	25	6	9
6	30	8	12
7	35	10	15
8	40	12	20
9	45	15	25
10	50	20	30

5.2 Adjustment of parameters

To adjust the parameters for the proposed algorithms, Taguchi method has been used with 9 experiments. Initial population number, maximum, mutation coefficient and crossover coefficient have be considered as parameters for NSGA-II method, as shown in Table 5.

Table 3: Probability distribution function to generate parameters

Variable	**U (a , b)**
c_i^k	U (10000 , 18000)
s_j^k	U (1.5 , 2.5)
$\tilde{s}_{ij}^k$	U (7 , 10)
$\widetilde{sa}_j^k$	U (0.2 , 0.3)
ε^k	U (1 , 2.5)
q_j^k	U (4 , 6)
$\tilde{q}_{ij}^k$	U (2 , 3)
$\widetilde{qa}_j^k$	U (0.3 , 0.6)
δ^k	U (3 , 10)
Atr_{ij}^{lk}	Time: U (1 , 4) Quality: U (0.1 , 0.25) Cost: U (40 , 100)
g_j^{lk}	U (0.1 , 0.4)
RNM_{fj}	U (0 , 0.4)

Table 5: Results of parameters setting for NSGA-II

	Mutation rate	**Compound rate**	**Initial population**	**Number of repetitions**
Results	0.3	0.7	30	125

For MOHS method, initial population number, maximum, harmony memory coefficient, rate of step setting and bandwidth rate have been considered as parameters, as shown in Table 6.

Table 6: Results of parameters setting for MOHS

	Bandwidth rate	**Rate of step setting**	**Harmony Memory**	**Initial population**	**Number of repetitions**
Results	2	0.4	0.6	30	125

5.3 Comparative indexes

There are two main types of metrics for evaluation of the performance of meta-heuristic algorithms:

1) Convergence metrics
2) Scattering metrics

Six matrices, which are a combination of matrices of both major groups, have been used for comparison in this work. The criteria of the first group are Pareto response, deviation from the ideal response, covering categories and the criteria of the second group are spacing, diversity, and maximum development. Algorithm execution time (Time*) has also been considered for comparison of computational requirements.

5.4 Analysis of the results of the proposed algorithms

Four problems of small dimensions have been considered here to show the efficiency of the proposed algorithms. The results obtained from the proposed algorithms have been compared with those of the exact solution of ε-constraint. In the exact solution of ε-constraint, 5 breaks have been considered for the objective constrained function and a maximum of 25 Pareto points are generated for each problem. However, the exact solution of ε-constraint is not capable of being solved in large dimensions due to the problem being NP-Hard. Thus, the problem will be solved in small dimensions. The results obtained by comparing ε-constraint, NSGA-II and MOHS methods are shown in Tables 4-5. In these tables, the first column on the left gives the problem specifications and the results obtained from ε-constraint method and solution time are given in the next 4 columns. The values for meta-heuristic methods are shown in the fifth and sixth columns and the last three columns give the errors from these meta-heuristic methods in each of the objective functions. In order to evaluate the errors in the obtained results using the proposed algorithms (RG), the best results (BR) were first considered for each objective function and then the best responses of each algorithm (RA) were compared. This is shown in equation (14).

$$RG = \frac{BR - RA}{BR} \times 100 \tag{14}$$

As observed in Tables 7 and 8, the Lingo solving time increases exponentially with increased problem size and then greatly increases following the quantitative increase in the problem size. Therefore, ε-constraint algorithm cannot be applied for average and big problems. The results also indicate that MOHS algorithm has shown the least error in all three objective functions. The average error by this algorithm for the first objective function is less than 1 and 2 % and less than 2% for the second objective function.

Table 7: Comparison of the results of procedures NSGA-II and ε-constraint

Problem	**ε-constraint**				**NSGA-II**				**Error (RG)%**		
	Time	***Quality***	***Cost***	***Time****	***Time***	***Quality***	***Cost***	***Time ****	***Time***	***Quality***	***Cost***
1	23.47	171.19	4682	56	17.62	128.11	3344	11.58	24.9	25.1	28.6
2	48.3	383.3	10802	316	33.72	247.5	7003	19.3	30.2	35.4	35.2
3	103.85	867.9	23319	2183	57.66	414.57	11069	28.4	44.5	52.2	52.5
4	147.39	1340.8	35878	13613	74.71	577.9	15153	35.58	49.3	56.9	57.8

Table 8: Comparison of the results of procedures MOHS and ε-constraint

Problem	**ε-constraint**				**MOHS**				**Error (RG)%**		
	Time	***Quality***	***Cost***	***Time****	***Time***	***Quality***	***Cost***	***Time****	***Time***	***Quality***	***Cost***
1	23.47	171.19	4682	56	23.47	171.19	4682	10.35	0	0	0
2	48.3	383.3	10802	316	48.06	383.3	10802	18.32	0.5	0	0
3	103.85	867.9	23319	2183	102.5	849.7	23110	28.16	1.3	2.1	0.9
4	147.39	1340.8	35878	13613	144.3	1316.7	35197	36.29	2.1	1.8	1.9

Ten problems of different dimensions have been considered in this work in which the number of activities, risks and response strategies are in the ranges of 8-50, 3-20, and 4-30, respectively. Prior to the analysis of the results of the criteria obtained for each algorithm, it is notable that higher values are more desirable for the two matrices of the number of non-dominating responses and diversity criteria. For the deviation from the ideal response criterion, higher values are more desirable considering that the objective functions are maximum whereas lower values are more desirable for the spacing criterion. Lower values are more desirable for time criterion. The values of each of the criteria are shown in Tables 9-10.

Table 9: Computational results of NSGA-II for sample problems

Problem	MID	NOP	Time*	Spacing	Diversity
1	4511.85	12	11.58	0.984	52.88
2	11339.35	50	19.3	0.76	237.4
3	19435.8	68	28.4	0.588	368.81
4	28002.7	60	35.58	0.5	349.74
5	45694.4	44	50.67	0.66	374.28
6	96925.9	85	87.05	0.62	700.61
7	169552.5	86	137.87	0.558	793.96
8	269635	43	218.19	0.555	562.4
9	452452.64	134	365.45	0.557	1569.86
10	846900.1	182	627.56	0.496	2088.2

Table 10: Computational results of MOHS for sample problems

Problem	MID	NOP	Time*	Spacing	Diversity
1	6366.04	5	10.35	0.878	38.9
2	17473.08	9	18.32	0.58	74.3
3	40620.1	5	28.16	0.528	80.04
4	65027.8	6	36.29	1.5	135.49
5	114589.74	5	56.5	0.92	72.24
6	314177.65	7	106.5	0.453	156.45
7	684026.48	7	182.1	1.02	237.41
8	1435183.54	7	298.54	0.886	256.34
9	2979159	5	474.11	1.086	281.66
10	1896170	28	882	0.979	1475.26

The Pareto diagram obtained from both algorithms for a problem with 12 activities, 5 response strategies and 4 risks is given in Figs. 3-4. As observed, the range of the objective function for harmony search algorithm is 69-71.5 while this range is 46-52 for the objective function in NSGA-II algorithm. In addition, the range of the second objective function for harmony search algorithm is 580-640 while this range is 360-420 for NSGA-II. The range of the third objective function for harmony search algorithm is 17000-18000 while this range is 10000-12000 for NSGA-II. As observed, the ranges of all three objective functions in MOHS algorithm are better than those in NSGA-II and the Pareto responses obtained by harmony search algorithm are more optimized.

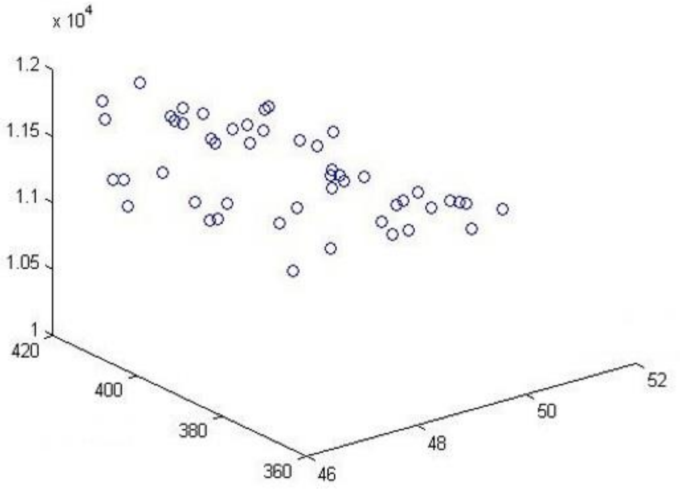

Figure 3. Pareto chart for problem with 12 activities, 5 risk response strategies and 4 risks for NSGA-II

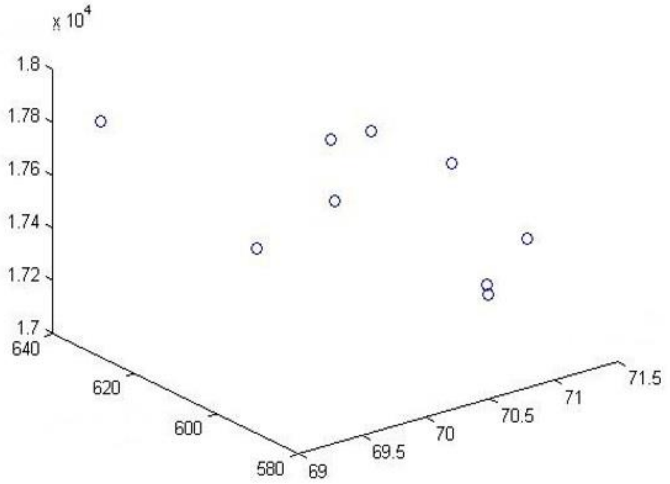

Figure 4. Pareto chart for problem with 12 activities, 5 risk response strategies and 4 risks for MOHS

The Pareto diagram obtained from both algorithms for a problem with 35 activities, 15 response strategies and 10 risks is given in Figs. 5-6. As observed, the range of the objective function for harmony search algorithm is 2420-2480 while this range is 670-710 for the objective function in NSGA-II algorithm. In addition, the range of the second objective function for harmony search algorithm is 24500-24700 while this range is 5800-6600 for NSGA-II. The range of the third objective function for harmony search algorithm is 676000-688000 while this range is 165000-175000 for NSGA-II. As observed, the ranges of all three objective functions in MOHS algorithm are better than those in NSGA-II and the Pareto responses obtained by harmony search algorithm are more optimized.

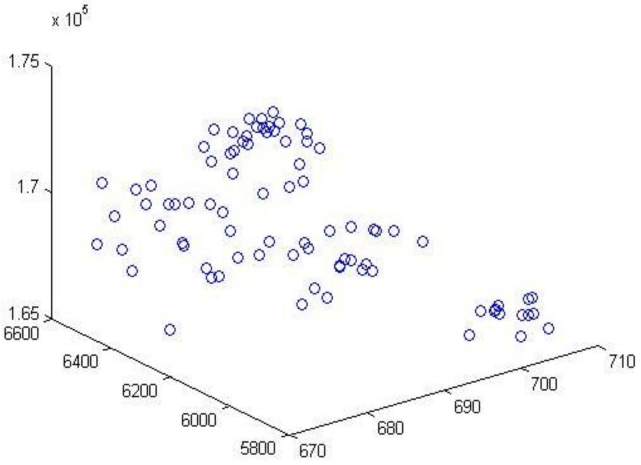

Figure 5. Pareto chart for problem with 35 activities, 15 risk response strategies and 10 risks for NSGA-II

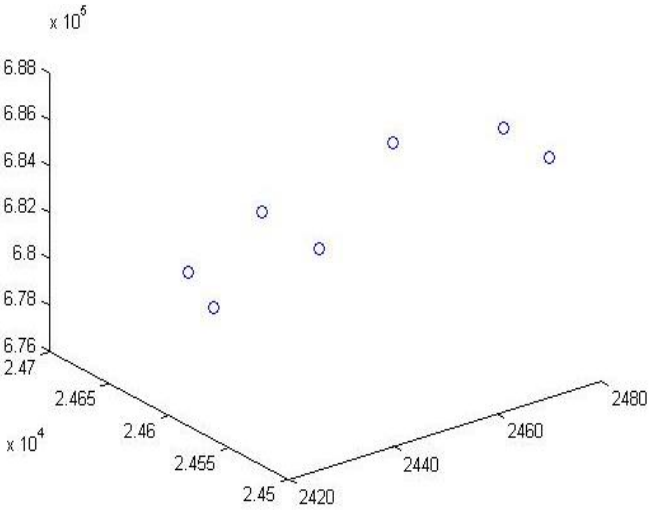

Figure 6. Pareto chart for problem with 35 activities, 15 risk response strategies and 10 risks for MOHS

Finally, to investigate the exact performance of the proposed algorithms and reach a scientific conclusion, hypothesis methods and testing have been used. Comparison of algorithms using statistical analyses is required for more desirable investigation of algorithms. Hypothesis testing of equality of the average of two bilateral communities has been used such that the null hypothesis is taken for the equality of the averages of evaluation criterion in both algorithms with a 95% confidence level. If the p-value obtained is smaller than 0.05 (1-0.95), the null hypothesis is rejected and it is concluded that there is a significant difference between the evaluation criterion for both algorithms and vice versa. Table 11 gives the statistical specifications of the corresponding five criteria for both algorithms.

Table 11: Statistical characteristics of the seven criteria for MOHS and NSGA-II

	Section	**N**	**Mean**	**Std. Deviation**	**Std. Error Mean**
Spacing	NSGA-II	10	0.6278	0.14754	0.04666
	MOHS	10	0.8830	0.30804	0.09741
Diversity	NSGA-II	10	709.8140	639.59888	202.25893
	MOHS	10	280.8090	428.27225	135.43158
MID	NSGA-II	10	194445.0240	270413.06432	85512.11923
	MOHS	10	755279.3430	1022637.49534	323386.37060
NOP	NSGA-II	10	76.4000	49.42379	15.62917
	MOHS	10	8.4000	7.01110	2.21711
Time*	NSGA-II	10	158.1650	199.04294	62.94290
	MOHS	10	209.2870	279.69578	88.44757

The third column in Table 12 shows p-values. As observed, two p-values have been calculated for each criterion. The first p-value is for hypothesis testing of the standard deviations of the two communities. The second value must be used otherwise. As Table 12 shows, if p-value=0.05, the performance of the algorithms for time, deviation from the ideal response and diversity criteria has no significant difference. However, the average of NSGA-II algorithm shows better performance in time and diversity criteria because it has a smaller time average and higher variation average. MOHS algorithm shows better performance in deviation from the ideal response criterion because it has a higher average. However, these advantages are not sensibly confirmed.

Table 12: Statistical hypothesis test results of comparison of the performance MOHS and NSGA-II

		t-test for Equality of Means						
		T	**df**	**Sig. (2-tailed)**	**Mean Difference**	**Std. Error Difference**	**95% Confidence Interval of the Difference**	
							Lower	**Upper**
Spacing	**Equal variances assumed**	-2.363	18	0.030	-.25520	0.10801	-0.48212	-0.02828
	Equal variances not assumed	-2.363	12.923	0.035	-.25520	0.10801	-0.48868	-0.02172
Diversity	**Equal variances assumed**	1.762	18	0.095	429.00500	243.41402	-82.38888	940.39888
	Equal variances not assumed	1.762	15.720	0.097	429.00500	243.41402	-87.75868	945.76868
MID	**Equal variances assumed**	-1.677	18	0.111	-560834.3	334501.22	-1263595.3	141926.66
	Equal variances not assumed	-1.677	10.252	0.124	-560834.3	334501.22	-1303669.1	182000.54
NOP	**Equal variances assumed**	4.308	18	0.000	68.00000	15.78565	34.83559	101.16441
	Equal variances not assumed	4.308	9.362	0.002	68.00000	15.78565	32.49980	103.50020
Time*	**Equal variances assumed**	-0.471	18	0.643	-51.12200	108.55774	-279.19334	176.94934
	Equal variances not assumed	-0.471	16.255	0.644	-51.12200	108.55774	-280.96099	178.71699

The performances of algorithms are significantly different in spacing and number of Pareto responses criteria when p-value=0.05 and NSGA-II algorithm has a better performance in both criteria because the average of NSGA-II algorithm is higher in the number of Pareto responses criterion and lower in spacing criterion. However, the performances of algorithms are significantly different in diversity criterion when p-value is greater than 0.095 and NSGA-II algorithm has a better performance in this criterion because the average of NSGA-II algorithm is higher in this criterion. The performances of algorithms are significantly different when p-value is over 0.11 and MOHS algorithm has a better performance because the average of this algorithm is higher. Therefore, it can be concluded that the responses from MOHS algorithm are more optimized than those from NSGA-II, but NSGA-II algorithm generates more diverse and convergent responses.

According to the results of the proposed algorithms, a case study related to this research will be presented.

In the present work, the model developed in "Design, Construction and Commissioning of Pilot Plant for Delayed Coking Process" project in the Research Institute of Petroleum Industry (RIPI) in Iran was used and its validation was tested. There are 6 activities, 4 risks and 10 risk responses in the project. In addition, three criteria; namely cost, quality and time were considered and these objectives were planned to be optimized. Tables 13-15 show the project activities, risks and risk responses.

Table 13: Project activities based on WBS

Activity	**Description**
1	Conceptual design of the pilot plant
2	Basic design of the pilot plant
3	Detailed design of the pilot plant
4	Monitoring the procurement, construction and installation of the pilot plant
5	Pre-commissioning and commissioning of the pilot plant
6	Solving the potential problems and preparation of the report

Table 14: Description of identified project risks

Risk	**Risk description**
1	Providing misinformation on design by the contractor
2	Disorder in providing the financial resources
3	Incompatibility of the received equipment with the approved engineering documents
4	Inadequate human resource expertise

Sets B1, B2 and B3 show the response sets, which may lead to synergism in the response effects on cost, quality and time criteria, if selected simultaneously.

Table 15: Description of risk responses in the project studied

Response	Description
A1	Review of timing for procurement of the main equipment based on planning
A2	Careful control of the design documents
A3	Planning and holding training courses for contractors and employees
A4	Signing contracts with consultation companies for modification of the equipment design
A5	Review of paying system
A6	Preparation of a comprehensive data bank for suppliers and contractors
A7	Substitution of some imported equipment with similar domestic ones
A8	Development and implementation of the management selection system
A9	Design and application of cost evaluation and budgeting
A10	Application of contingency reserves (unallocated funds)

The results obtained in this case study show that the proposed model is efficient. In fact, this model greatly helps managers of oil, gas and petroleum projects choose risk response strategies based on their interactions.

6. DISCUSSION AND CONCLUSION

An integer linear programming model has been proposed in this work to overcome the problem of selection of risk responses for project risks. This model attempts to choose proper responses for different risks based on optimization of the criteria considered in the objective function. The objective function of this problem is capable of including and optimizing the different desired criteria in the project. Unlike other works, time constraints, quality and the relationships between different risk responses; especially interactions between risks, have been considered in this study. The interactions and relationships are such that a positive or negative synergism between the responses is activated if a known number of responses are selected. Contrary to what is assumed, the interactions between risks were observed to be very effective on this synergism. Assessment of the interactions between risks is performed by Risk Structure Matrix (RSM) method consisting of methods such as Design Structure Matrix (DSM) and Analytic Hierarchy Process (AHP). In addition, limitations due to prerequisites, co-requisites and the balance of selected risk responses have also been considered. The ε-constraint method, Non-dominated Sorting Genetic and Multi Objective Harmony Search Algorithms have been used to solve the model and cost, time and quality criteria have been considered as evaluation criteria in the objective function. To solve the model, a Pareto diagram was first used for analysis. The obtained Pareto responses have been optimized using the Multi Objective Harmony Search Algorithm.

To perform an exact evaluation of the performances of these algorithms and reach a scientific conclusion, hypothesis testing and methods were used next. Hypothesis testing of equality of the average of two bilateral communities has been used such that the null hypothesis is taken for the equality of the averages of evaluation criteria in both algorithms with a 95% confidence level. It was finally observed that the responses from Multi Objective Harmony Search Algorithm are more optimized, but Non-dominated Sorting Genetic generated more various and convergent responses. The outcomes of the responses show that this model will enable project managers to predict proper responses before execution of the project to increase the desirable effects of these responses as a strong tool. For a future investigation, we can consider the analysis of an uncertain model with a new meta-heuristic algorithm.

REFERENCES

[1] Danielsson J, James KR, Valenzuela M, Zer I. Model Risk of Risk Models, *J Finan Stabil* 2016; **23**: 79-91.

[2] Aldaihani MM, Al-Deehani TM. Mathematical models and a tabu search for the portfolio management problem in the Kuwait stock exchange, *Int J Operat Res* 2010; **7**(4): 445-62.

[3] Wu D, Dai Q, Zhu X. Measuring the effect of project risks based on shapley value for project risk response, *Proced Comput Sci* 2016; **91**: 774-8.

[4] Buchan DH. Risk analysis-some practical suggestions, *Cost Eng* 1994; **36**: 29-34.

[5] Miller R, Lessard D. Understanding and managing risks in large engineering projects, *Int J Project Manag* 2001; **19**(8): 437-43.

[6] Zou P, Zhang G, Wang J. Understanding the key risks in construction projects in China, *Int J Project Manag* 2007; **25**(6): 601-14.

[7] Ben-David I, Raz T. An integrated approach for risk response development in project planning, *J Operat Res Society* 2001; **52**(1): 14-25.

[8] Fan M, Lin NP, Sheu C. Choosing a project risk-handling strategy: an analytical model, *Int J Product Econom* 2008; **112**(2): 700-13.

[9] Ren H. Risk lifecycle and risk relationships on construction projects, *Int J Project Manag* 1994; **12**(2): 68-74.

[10] Ackermann F, Eden C, Williams T, Howick S. Systemic risk assessment: a case study, *J Operat Res Society* 2007; **58**(1): 39-51.

[11] Baccarini D. The concept of project complexity-a review, *Int J Project Manage* 1996; **14**(4): 201-4.

[12] Williams TM. The need for new paradigms for complex projects, *Int J Project Manag* 1999; **17**(5): 269-73.

[13] Kwan T, Leung H. A risk management methodology for project risk dependencies, *IEEE Transact Softw Eng* 2011; **37**(5): 635-48.

[14] De Almeida AT, Alencar MH, Garcez TV, Ferreira RJP. A systematic literature review of multicriteria and multi-objective models applied in risk management, *IMA J Manag Mathemat* 2016; **28**(2): 153-84.

[15] Fang C, Marle F. A simulation-based risk network model for decision support in project risk management, *Decis Support Syst* 2012; **52**(3): 635-44.

[16] Paquin JP, Tessier D, Gauthier C. The effectiveness of portfolio risk diversification: an additive approach by project replication, *Project Manag J* 2015; **46**(5): 94-110.

[17] Adner R. Match your innovation strategy to your innovation ecosystem, *Harvard Business Rev* 2006; **84**(4): 98–107.

[18] Manoj UV, Dawande M, Rajamani D, Sriskandarajah C. Mitigating the risk of supply disruptions: a case study, *Int J Operat Res* 2009; **5**(2): 131-51.

[19] Dikmen I, Birgonul MT, Anac C, Tah JHM, Aouad G. Learning from risks: A tool for post-project risk assessment, *Automat Construct* 2008; **18**(1): 42-50.

[20] López C, Salmeron JL. Risks response strategies for supporting practitioners decision-making in software projects, *Proced Technolo* 2012; **5**: 437-444.

[21] Fatah KS, Shi P, Ameen JRM, Wiltshire R. Risk averse preference models for normalized lotteries based on simulation, *Int J Operat Res* 2010; **8**(2): 189-207.

[22] Taaffe K, Chahar K, Tirumalasetty D. Risk averse selective newsvendor problems, *Int J Operat Res* 2008; **3**(6): 681-703.

[23] Zhang Y, Fan ZP. An optimization method for selecting project risk response strategies, *Int J Project Manag* 2014; **32**(3): 412-22.

[24] Datta S, Mukherjee SK. Developing a risk management matrix for effective project planning-an empirical study, *Project Manag J* 2001; **32**(2): 45-57.

[25] Hatefi MA, Seyedhoseini SM, Noori S. Risk response actions selection, *Int J Appl Manag Technol* 2007; **5**(1): 385-408.

[26] Kujawski E. Selection of technical risk responses for efficient contingencies, *Syst Eng* 2002; **5**(3): 194-212.

[27] Pipattanapiwong J, Watanabe T. Multi-party risk management process (MRMP) for a construction project financed by an international lender, *Proceedings of the 16th Association of Researchers in Construction Management (ARCOM) Annual Conference*, Glasgow, Scotland, 2000.

[28] Haimes Y. A Unified Framework for Risk Assessment and Management of Sanitary and Phytosanitary (SPS) Situations, Working paper, Center for Risk Management of Engineering Systems, University of Virginia, 2005.

[29] Klein JH. Modelling risk trade-off, *J Operat Res Society* 1993; **44**(5): 445-60.

[30] Chapman CB. Large engineering project risk analysis, *IEEE Transact Eng Manag* 1979; **26**(3): 78-86.

[31] Seyedhoseini SM, Noori S, Hatefi MA. An integrated methodology for assessment and selection of the project risk response actions, *Risk Anal* 2009; **29**(5): 752-63.

[32] Klein JH, Powell PL, Chapman CB. Project risk analysis based on prototype activities, *J Operat Res Society* 1994; **45**(7): 749-57.

[33] Ben-David I, Rabinowitz G, Raz T. *Economic Optimization of Project Risk Management Efforts*, The Israel Institute of Business Research, 2002.

[34] Kayis B, Arndt G, Zhou M, Amornsawadwatana S. A risk mitigation methodology for new product and process design in concurrent engineering projects, *Annals CIRP* 2007; **56**(1): 167-70.

[35] Zhang Y. Selecting risk response strategies considering project risk interdependence, *Int J Project Manag* 2016; **34**(5): 819-30.

[36] Flanagan R, Norman G. *Risk Management and Construction*, Blackwell, Oxford, 1993.

[37] Elkjaer M, Felding F. Applied project risk management-introducing the project risk management loop of control, *Int Project Manag J* 1999; **5**(1): 16-25.

[38] Piney C. *Risk Response Planning: Select the Right Strategy*, Fifth Project Management Conference, France (2002).

[39] Chapman CB, Ward SC. *Project Risk Management*, Processes, Techniques and Insights, John Wiley, Chichester, UK, 1997.

[40] Soofifard R, Khakzar Bafruei M. An optimal model for project risk response portfolio selection (P2RPS) (case study: research institute of petroleum industry), *Iranian J Manag Studies* 2016a; **9**(4): 741-65.

[41] Soofifard R, Khakzar Bafruei M. Fuzzy multi-objective model for project risk response selection considering synergism between risk responses, *Int J Eng Manag Econom* 2016b; **6**(1): 72-92.

[42] Steward D. The design structure matrix: a method for managing the design of complex systems, *IEEE Transact Eng Manag* 1981; **28**(3): 71-4.

[43] Fang C, Marle F, Zio EJB. Network theory-based analysis of risk interactions in large engineering projects, *Reliabi Eng Syst Safe* 2012; **106**: 1-10.

[44] Fang C, Marle F, Xie M, Zio E. An integrated framework for risk response planning under resource constraints in large engineering projects, *IEEE Transact Eng Manag* 2013; **60**(3): 627-39.

[45] Saaty T. *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*, McGraw-Hill, New York International Book Company, 1980.

[46] *PMI "A Guide to the Project Management Body of Knowledge (PMBOK Guide)"*, 4th Edition, USA: Project Management Institute Inc, Newtown Square, Pa, 2008.

[47] Marle F, Vidal L, Bocquet J. Interactions-based risk clustering methodologies and algorithms for complex project management, *Int J Product Econom* 2013; **142**(2): 225-34.

[48] Eppinger S, Whitney D, Smith R, Gebala D. A model-based method for organizing tasks in product development, *Res Eng Des* 1994; **6**(1): 1-13.

[49] Chen SJ, Lin L. Decomposition of interdependent task group for concurrent engineering, *Comput Indust Eng* 2003; **44**(4): 435-59.

[50] Saaty T. A scaling method for priorities in hierarchical structures, *J Mathemat Psychol* 1977; **15**(3): 234-81.

[51] Haimes YY, Lasdon LS, Wismer DA. On a bicriterion formulation of the problems of integrated system identification and system optimization, *IEEE Transact Syst* 1971; **1**(3): 296-7.

[52] Deb K, pratap A, Agrwal S, Meyarivan T. A fast and elitist multi objective genetic algorithm: NSGA-II, *IEEE Transact Evolut Comput* 2002; **6**(2): 182-97.

[53] Geem ZW, Kim JH, Loganathan GV. A new heuristic optimization algorithm: harmony search, *Simulat* 2001; **76**(2): 60-8.

[54] El-henawy I, Abdel-Raouf O, Abdelbaset M. Improved harmony search algorithm with chaos for solving definite integral, *Int J Operat Res* 2014; **21**(2): 252-61.