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A hybrid mathematical programming model for optimal project portfolio selection using fuzzy inference system and analytic hierarchy process

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ABSTRACT

The primary goal in project portfolio management is to select and manage the optimal set of projects that contribute the maximum in business value. However, selecting Information Technology (IT) projects is a difficult task due to the complexities and uncertainties inherent in the strategic-operational nature of the process, and the existence of both quantitative and qualitative criteria. We propose a two-stage process to select an optimal project portfolio with the aim of maximizing project benefits and minimizing project risks. We construct a two-stage hybrid mathematical programming model by integrating Fuzzy Analytic Hierarchy Process (FAHP) with Fuzzy Inference System (FIS). This hybrid framework provides the ability to consider both the quantitative and qualitative criteria while considering budget constraints and project risks. We also present a real-world case study in the cybersecurity industry to exhibit the applicability and demonstrate the efficacy of our proposed method.

1. Introduction

Information Technology (IT) plays a significant role in an organization's ability to compete in the marketplace. Studies by Bosworth and Triplett (2000) and Brynjolfsson and Hitt (2000) report that the application of IT has significantly increased productivity in recent decades. A study on the impact of project portfolio management on IT projects conducted by De Reyck et al. (2005) on 34 medium-to large-size companies found that the adoption of project portfolio management processes had a significant positive impact on the return on the projects in the portfolio, and a significant negative impact on the number of project-related problems reported. This result is somewhat echoed in Rosacker and Olson (2008), who executed an empirical assessment of IT project selection and evaluation methods in the US public sector (state government) and found that financial methodologies seemingly have a significant effect in better controlling project cost. Thus, it is imperative for organizations to manage their IT project portfolios effectively, and more importantly to evaluate and select the most beneficial projects for the portfolios. Portfolio evaluation is the process of evaluating a set of homogenous projects with a common purpose (Wu et al., 2019). Fast development in IT has facilitated business between employees, customers, suppliers and partners. However, the quantitative and qualitative factors such as business goals, project risks and available resources have caused difficulties in the selection of IT projects. The investigation of these issues has given rise to studies that focus on the usage of different methods in tackling IT project portfolio selection. Tavana, Keramatpour, Santos-Arteaga, and Ghorbaniane (2015) show that often multi-criteria decision making (MDCM) models, mathematical models, or a combination of both are used to solve project portfolio selection problems. In the following, the project portfolio selection literature is explored with reference to MCDM methods, mathematical models, and combination of the two.

MCDM methods are commonly used to rank multiple alternatives according to multiple and often conflicting criteria (Mina, Mirabedini, Kian, & Ghaderi, 2014), thus making them suitable for solving project portfolio selection problems with complex and conflicting criteria. According to Wu, Zhang, Xu, and Li (2018), MCDM models are widely used for project evaluation and ranking. Han, Kim, Choi, and Kim

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(1998) used a quality function deployment-based method to determine information system development priority while considering the alignment between business strategy and information systems. Stewart and Mohamed (2002) developed a multi-criteria decision theory-based approach to select IT projects using business value and risk criteria. The advantage of their approach is that it allows decision makers to define their preferences in a set of tangible and intangible metrics in utility functions. Kulak, Kahraman, Öztaysi, and Tanyas (2005) took on the problem of multi-attribute IT project selection using fuzzy axiomatic design. Their proposed approach was able to use both complete and incomplete information for comparing communication systems, where fuzzy method was used for incomplete information and crisp method was used for complete information. The problem studied had five criteria: technical and organizational risk, return on investment, user satisfaction, operational agility and strategic competitiveness.

Lee, Chen, and Chang (2008) presented an approach based on Fuzzy Analytic Hierarchy Process (FAHP) and balanced scorecard to evaluate the IT department in a manufacturing industry. They considered a comprehensive evaluation framework based on four points of view: financial, customer, internal business process, and learning and growth. However, they ignored the relationship between the criteria. A comprehensive and systematic approach for enterprise information system project selection was implemented using the Analytic Network Process (ANP) method by Liang and Li (2008). Employing the benefits, costs, opportunities, and risk, criteria and considering their internal dependence, they proposed a comprehensive approach and measured its effectiveness in the undershirt manufacturing industry. A hybrid approach based on Analytic Hierarchy Process (AHP) and Gray-The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was developed by Oztaysi (2014) to select the content management system using tangible and intangible criteria. Content management system is a key IT process that links the external and internal environment in organizations. They used the AHP method to calculate the weight of the criteria and then rank alternatives with Gray-TOPSIS. Oztaysi (2015) presented an interval type-2 FAHP approach for enterprise information system project evaluation and selection. Due to the interval of fuzzy scales, the proposed approach has a high degree of flexibility. They implemented their method in work-wear manufacturing industry.

Uygun, Kaçamak, and Kahraman (2015) presented an integrated approach combining ANP and Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods to evaluate the outsourcing providers in the telecommunication industry. The DEMATEL technique was used to determine the criteria interdependences and the fuzzy ANP method for calculating the weights of the criteria and sub-criteria. Rodríguez, Ortega, and Concepción (2017) developed an approach for selecting the most appropriate option for risk management in IT projects in line with the needs of the organization. In other words, they developed the reportedly simpler and more intuitive graphical vectorial approach as a multi-criteria tool for managerial decision-making. Their purpose was to identify appropriate risk management criteria in IT projects and used a strategic approach to this end. Pramanik, Mondal, and Haldar (2019) used a fuzzy Shannon entropy and fuzzy TOPSIS-based approach to evaluate and select information systems projects. Using fuzzy entropy method, they determined the weight of the criteria and then alternatives were ranked by the fuzzy TOPSIS method. Zou, Duan, and Deng (2019) presented a decision support system using the concepts of fuzzy MCDM and applied it on information systems project evaluation. They provided a sustainable approach considering three dimensions of economic, social and environmental as their main contribution. However, they did not consider the relationship between criteria or explored any specific case studies.

Alongside MCDM methods, there have been studies that utilize approaches based on mathematical models, which come into play when project selection is conducted to optimize one or more specific objective functions while considering specific constraints (Perez & Gomez, 2016). Santhanam, Muralidhar, and Schniederjans (1989) are the pioneers in considering the problem of information system project selection using mathematical models. They proposed a multi-objective programming model and used the goal programming approach to solve their model. Similarly, Santhanam and Kyparisis (1996) presented a non-linear multi-objective model for the information system project selection considering the resource constraints and technical interdependencies between the projects. They also used the goal programming approach to solve this problem. Badri, Davis, and Davis (2001) proposed a mixed 0–1 goal programming model which they applied to a real-world information system project selection problem.

Sowlati, Paradi, and Suld (2005) presented a linear programming model within a Data Envelopment Analysis (DEA) to prioritize information system projects. A mathematical model based on the DEA method for enterprise resource planning systems selection was developed by Ghapanchi, Jafarzadeh, and Khakbaz (2008). The performance of their model heavily depends on the experience of the experts and the evaluation criteria; however, it is not applicable for implementation in large organizations. Asosheh, Nalchigar, and Jamporazmey (2010) used DEA and balanced scorecard to evaluate IT projects. They first utilized the balanced scorecard approach to determine the evaluation criteria of IT projects, and thereafter utilized DEA to rank the projects. Ghapanchi, Tavana, Khakbaz, and Low (2012) proposed a method to select portfolios of projects with interdependencies. The authors used DEA to simultaneously select the best portfolio of projects while taking into consideration both project interactions and project uncertainties, which were modelled as fuzzy variables. A new DEA method was developed by Toloo, Nalchigar, and Sohrabi (2018) for informationsystem design and evaluation. The advantage of their model is that it is possible to consider subjective opinions and intuitive senses by the decision maker in the model. The results of comparing the performance of the model with the data set used in other models and implementing it in a real-world problem, indicates its effectiveness.

There have also been studies that applied a combination of MCDM and mathematical programming models for project evaluation and selection problems. This hybrid approach is sometimes preferred as individual techniques possess unique advantages that allow for complimentary contribution (Govindan, Rajendran, Sarkis, & Murugesan, 2015). For example, integrating fuzzy logic with quantitative models aids in handling the uncertainties inherent in real-world problems (Zavadskas, Govindan, Antucheviciene, & Turskis, 2016). Hybrid approaches are also applicable when projects are not of the same importance. In this case, the value of each project is first calculated using MCDM methods, where the output is considered as input for the mathematical model, which performs the project selection. This combination allows us to take both operational and strategic decisions into account (Tavana et al., 2015).

Schniederjans and Wilson (1991) applied AHP within a goal programming framework. They used AHP to prioritize the projects into a ranked list, which is then used as input for the goal programming model. Lee and Kim (2000) developed a method combining ANP and mathematical programming model. They used goal programming to solve their mathematical model. In line with the previous study, Lee and Kim (2001) presented an integrated hybrid approach based on the Delphi, ANP, and 0–1 goal programming approach in order to evaluate and select information system projects, taking the interdependent relationship between the projects into account. The Delphi method was used to collect group opinion and the weight of the criteria was calculated using the ANP method. Finally, a mathematical model was developed for selecting the projects using the goal programming approach.

Zandi and Tavana (2010) proposed a comprehensive Multi-Objective Decision-Making (MODM) - Multi-Attribute Decision-Making (MADM) approach to solve a portfolio selection problem with IT projects having both quantitative and qualitative attributes as well as having interdependencies among them. MADM was used to rank the projects according to multiple attributes, and MODM was used to derive a vector optimization-based solution. Tavana et al. (2015) presented an integrated three-stage hybrid approach for project evaluation and selection. The first stage uses DEA to screen the available projects, the second stage ranks the projects using TOPSIS and the third stage uses an integer linear programming model to select the most suitable project portfolio. Sagnak and Kazancoglu (2019) presented the FANP method combined with 0–1 goal programming to select the most appropriate enterprise resource planning software. Criteria weights were calculated by fuzzy ANP and then the optimum alternative was selected by mathematical model.

The studies that propose hybrid methods all have one thing in common: their approaches divide the task into evaluating the projects using MCDM techniques before performing project selection via a mathematical model. Our proposed method too follows this system. We present a two-stage approach that combines FAHP, Fuzzy Inference System (FIS) and 0–1 programming model methods. In the first stage, the weights of the criteria are calculated by the FAHP method and the score of the evaluation of each project is determined by FIS. Using the knowledge of the experts, FIS carefully considers the interdependencies between the criteria and uses the fuzzy inference rules to measure the performance of each project. In the second stage, a three-objective mathematical model including maximizing the profit, maximizing the total value of the project portfolio, and minimizing the risk, simultaneously, are presented. We evaluate the effectiveness and efficacy of our proposed approach by implementing it on a real-world problem and by performing sensitivity analysis on the obtained solution respectively.

There has been a multitude of different MCDM methods used to evaluate projects in the literature. Our method of combining FAHP and FIS to evaluate the projects uses nonlinear relations, which allows for a more accurate approximation of measurements. FAHP integrates AHP with fuzzy logic, which both allows for appropriate expression of linguistic evaluation (Mardani, Jusoh, & Zavadskas, 2015) and aids in dealing with uncertainties inherent in real-world decision-making problems (Li, Huang, & Chen, 2011). These characteristics make FAHP suitable for solving problems, such as project evaluation for portfolio selection, that involve subjective evaluations. In fact, literature review studies by Kahraman, Onar, and Oztaysi (2015) and Mardani et al. (2015) report that FAHP is the most widely used MCDM method in the fields of business, management and accounting.

FIS is a nonlinear system that combines expert system technology with fuzzy logic. FIS consists of a collection of fuzzy IF-THEN rules, which are defined based on the knowledge of the experts or decision-makers. FIS uses these rules to simulate the human reasoning process. Advantages of FIS include the allowance of effective usage of human knowledge and the rules being easily modifiable to reflect the judgment of experts (Cherkassky, 1998; Rodríguez, Ortega, & Concepción, 2016). Studies that have utilized FIS include those by Amindoust, Ahmed, Saghafinia, and Bahreininejad (2012) who ranked sustainable suppliers, Tavana, Azizi, Azizi, and Behzadian (2013) who tackled player selection and team formation in multi-player sports, Bermudez Peña, Lugo García, Pérez, and Yobanis (2015) who used adaptive network-based FIS in project evaluation, and Rodríguez et al. (2016) who addressed the problem of risk evaluation in IT projects.

The following section contains the problem statement along with an introduction to our proposed approach. The section after is dedicated to the implementation of the proposed model in a specific case study, and includes discussion on the results obtained. The fourth section explores performing sensitivity analysis on the previously obtained solution. The final section concludes our study.

2. Problem statement and our proposed approach

Most IT project-based companies are heavily dependent on project revenues as their major source of income. Thus, one of their major concerns is the selection of optimal portfolio of projects, as a set of appropriate projects increases the profitability of organization. Project portfolio selection does not only take profit from execution into account, but also other factors such as execution risk, organizational capability in project execution and the budget. Sometimes these evaluation criteria are in conflict with one another, hence making the project portfolio selection problems Multi Criteria Decision Making problems with conflicting criteria. Consequently, we present a two-stage hybrid decision support system based on FAHP, FIS and mathematical programming for the evaluation and selection of an optimal IT project portfolio.

The process begins, in stage one, with obtaining the relevant criteria and sub-criteria. FAHP is then utilized to weight the criteria as the criteria and sub-criteria have an existing hierarchy. Furthermore, FAHP has the ability to ignore the interdependencies between the criteria (based on expert opinions). The final score of each project is calculated through questionnaires and non-cost scores. These scores are set as inputs to FIS, after which the non-cost score of each project is determined. In stage two, a mathematical model (using the information from stage one) with the objectives of maximizing the value of selected portfolio (non-cost objective) and its profit (cost objective) subject to the budget constraint is developed. The process of our approach is presented in following sections.

2.1. Stage 1: score calculation

In this stage, we calculate the score of the risk and the strategic-operational performance of organizations for each project.

2.1.1. Step 1: extracting the criteria and their sub-criteria

A set of criteria are extracted from the literature and provided to experts, who are then able to select the appropriate criteria for the evaluation process considering the organization condition and features.

2.1.2. Step 2: weighting the sub-criteria

The experts are given pairwise comparison questionnaires, in which they compare the sub-criteria of each criteria (separately) using linguistic terms. The data obtained from the questionnaires are inputted as triangular fuzzy numbers (l,m,u) from the pairwise comparisons (according to Table 1) into the non-linear mathematical model (1) presented by Dağdeviren and Yüksel (2010). Note that one model is constructed for each criterion that has multiple sub-criteria.

Table 1
Linguistic scale for difficulty and importance.

Linguistic scales for difficulty	Linguistic scales for importance	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal	Just equal	(1, 1, 1)	(1, 1, 1)
Equally difficult (ED)	Equally importance (EI)	(1/2, 1, 3/2)	(2/3, 1, 2)
Weakly more difficult (WMD)	Weakly more importance (WMI)	(1, 3/2, 2)	(1/2, 2/3, 1)
Strongly more difficult (SMD)	Strongly more importance (SMI)	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very strongly more difficult (VSMD)	Very Strongly more importance (VSMI)	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolutely more difficult (AMD)	Absolutely more importance (AMI)	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

$$
\begin{aligned}
&Max\ \lambda\\
&s.\ t.\\
&(m_{ij}-l_{ij})\times\lambda\times w_j - w_i + l_{ij}\times w_j \le 0,\\
&(u_{ij}-m_{ij})\times\lambda\times w_j + w_i - u_{ij}\times w_j \le 0,\\
&\sum_{k=1}^{n} w_k = 1; \qquad w_k > 0 \text{ and } k = 1, 2, \ldots, n,\\
&i = 1, 2, \ldots, n-1; \quad j = 2, 3, \ldots, n \text{ and } j > i.
\end{aligned} \tag{1}
$$

where the indices i and j represent the row and column of the pairwise comparisons matrix, respectively. The solution to the model (1) yields both w_k which represents the weight of each sub-criterion k, and the λ value which serves an indication of the consistency of the data provided by the experts. The value of λ can be positive or negative. A positive λ means that the pairwise comparisons given by the experts are consistent and that their judgment is sound. A negative λ signifies that the pairwise comparisons given are inconsistent, in which case the experts are asked to reconsider their judgments and Step 2 is repeated.

2.1.3. Step 3: determining the score of each project

At first, for each one of the projects, the experts score each sub-criterion using the linguistic terms in Table 2. Finally, the score of each project is calculated by summing up over the product of sub-criteria weights and the evaluated value for the project.

2.1.4. Step 4: obtaining the final value of each project using FIS

We set the (previously obtained) project score of each criterion as input to FIS, which yields the system output of the score of each project.

2.2. Stage 2: Optimal project portfolio selection

In this stage, we construct a multi-objective zero-one mathematical model to select the optimal project portfolio with the following indices, parameters and variable:

Indices	
i	Project
Parameters	
SCR_i	Score of *ith project (obtained from FIS and FAHP)*
c_i	The expected costs of project i
I_i	The expected income of project i
r_i	The expected risks of project i
bg	Total available budget
Variable	
$x_i\begin{cases}1\\0\end{cases}$	If project i *is selected* Otherwise

$$Max\ Z^{benefit} = \sum_i (I_i - c_i)\times x_i \tag{2}$$

$$Max\ Z^{total\ value} = \sum_i SCR_i \times x_i \tag{3}$$

$$Min\ Z^{risk} = \sum_i r_i \times x_i \tag{4}$$

$s.\ t.$

$$\sum_i c_i \times x_i \le bg \tag{5}$$

The first objective function (Eq. (2)) maximizes the obtained profit from the project portfolio, the second objective function (Eq. (3)) maximizes the total value of the project portfolio, while the third objective function (Eq. (4)) minimizes the risk of the project portfolio selection. The constraint Eq. (5) ensures that the selected projects must not breach the available budget. Solving the proposed model will yield the optimal project portfolio of maximum profit and value that satisfies the budget constraint and minimizes projects risks. The structure of the proposed approach is illustrated in the flowchart in Fig. 1.

Table 2
Linguistic values and mean of fuzzy numbers.

Linguistic values for positive sub-factors	Linguistic values for negative sub-factors	Triangular fuzzy numbers	The mean of fuzzy numbers
Very weak	Very strong	(0,0,0)	0
Weak	Strong	(0,0.167,0.333)	0.167
Weak-Mid	Mid-Strong	(0.167,0.333,0.5)	0.333
Mid	Mid	(0.333,0.5,0.667)	0.500
Mid-Strong	Weak-Mid	(0.5,0.667,0.833)	0.667
Strong	Weak	(0.667,0.833,1)	0.833
Very strong	Very weak	(1,1,1)	1

3. Case study

In this section we present a real-life case study to demonstrate the applicability and efficacy of the method proposed in this study. Northern Cyber Security Systems (NCSS)[2] is a cyber-security company with over 6000 employees located in southern Pennsylvania that needs to evaluate ten large cyber security projects. These projects cover a wide range of cyber security activities including assess and plan, detect and protect, and respond and recover. Six project managers were selected to participate in this study. Table 3 presents a short summary of the ten projects considered in this study.

3.1. Stage 1: score calculation

3.1.1. Step 1: extracting the criteria and their sub-criteria

In this step, the qualitative and non-cost criteria are selected to evaluate the IT projects. Having reviewed studies by Liang and Li (2008), Oztaysi (2014, 2015), Pramanik et al. (2019), Stewart and Mohamed (2002), Tavana et al. (2015), Uygun et al. (2015), Zandi and Tavana (2010) a comprehensive set of evaluation criteria is gathered and these criteria are presented to the expert panel of project managers. Using the brainstorming method, the expert panel selected the most effective criteria and divided them into three categories: execution capability, on-time delivery, and alignment with organization strategies and objectives. The criteria and sub-criteria obtained are as follows:

- Execution capability (EC)
  - ○ Execution facility (EC1)
  - ○ Similar experiences (EC2)
  - ○ Level of workforce experience (EC3)
  - ○ Job description perception (EC4)
  - ○ Assurance in execution capability (EC5)
  - ○ Execution risks including capacity risk, financial risk, etc. (EC6)
- On-time delivery (OD)
  - The probability of employing a comprehensive plan for confronting with delay (OD1)
  - Schedule flexibility in the case of deviation from program (OD2)
  - Effective instruction for time estimation (OD3)
- Alignment with organization strategies and objectives (A)

Fig. 2 shows the hierarchical structure between the goal, criteria, sub-criteria and alternatives.

3.1.2. Step 2: weighting the sub-criteria

The sub-criteria of each criteria are weighted using the pairwise comparison matrix. Tables 4 and 5 respectively represent the pairwise comparisons for the criteria EC and OD.

These pairwise comparisons are then used as input in the non-linear model mathematical model (1). Recall that there is one mathematical model per criteria with multiple sub-criteria. The mathematical model

[2] The name of the company is changed to protect its anonymity.

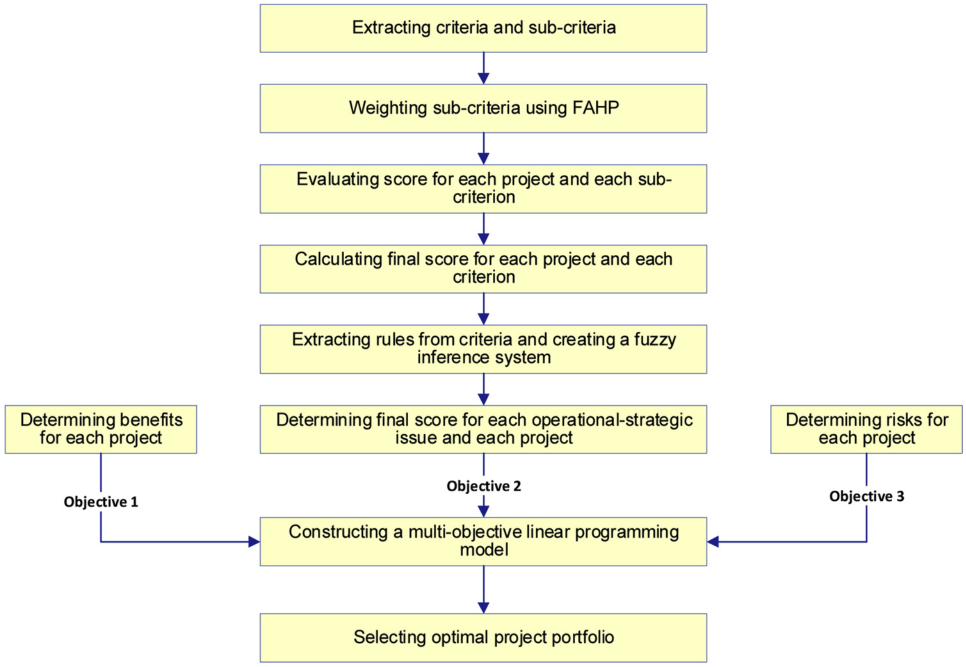


Fig. 1. The structure of our proposed framework.

Table 3
A short description of the projects considered in this study.

Project Number	Project Name	Project Description
1	VPS	Installation of a secured Virtual Private Server (VPS) for a state university in Northwestern Pennsylvania
2	H&SN	Implementation of a secured Hub-and-Spoke Network (H&SN) to connect 7 distribution centers for a delivery company located in Northwestern Pennsylvania.
3	QR-CP	Implementation of a secured QR-Code Payment (QR-CP) system for a bike-sharing company operating in a large Southern Pennsylvania municipality.
4	Advanced Communication Services	Installation of a secured audio/video system for a supermarket chain in Central Pennsylvania.
5	HDSL	Implementation of a secured High-bit-rate Digital Subscriber Line (HDSL) for wideband digital transmission within at the headquarters of an insurance company is Southern Pennsylvania.
6	Video Conference Infrastructure	Installation of secured video conferencing technology for online courses at a private university in Southern Pennsylvania.
7	Online Educational Networks	Implementation of a secured online educational network for the department of education at a local municipality in Western Pennsylvania.
8	National Health Network	Implementation of at a secured wireless network to connect to the National Health Network for healthcare workers, patients, and families at a pediatric care center in Central Pennsylvania.
9	AAA	Installation of a secured Authentication, Authorization, and Accounting (AAA) system for controlling access to computer resources at a Central Pennsylvania university.
10	VIOP	Implementation of a secured Voice over Internet Protocol (VoIP) services for a hospital in Southern Pennsylvania.

for the criteria EC (using the fuzzy-triangle numbers from Table 4) is as follows:

$$
\begin{array}{lll}
\textit{Max } \lambda & & \\
\textit{s.t} & \frac{1}{2}\lambda w_6 + w_1 - \frac{5}{2}w_6 \le 0 & \frac{1}{3}\lambda w_5 + w_3 - w_5 \le 0 \\
\frac{1}{2}\lambda w_2 - w_1 + 2w_2 \le 0 & \frac{1}{6}\lambda w_3 - w_2 + \frac{1}{2}w_3 \le 0 & \frac{1}{2}\lambda w_6 - w_3 + \frac{1}{2}w_6 \le 0 \\
\frac{1}{2}\lambda w_2 + w_1 - 3w_2 \le 0 & \frac{1}{3}\lambda w_3 + w_2 - w_3 \le 0 & \frac{1}{2}\lambda w_6 + w_3 - \frac{3}{2}w_6 \le 0 \\
\frac{1}{2}\lambda w_3 - w_1 + \frac{3}{2}w_3 \le 0 & \frac{1}{6}\lambda w_4 - w_2 + \frac{1}{2}w_4 \le 0 & \frac{1}{6}\lambda w_5 - w_4 + \frac{1}{2}w_5 \le 0 \\
\frac{1}{2}\lambda w_3 + w_1 - \frac{5}{2}w_3 \le 0 & \frac{1}{3}\lambda w_4 + w_2 - w_4 \le 0 & \frac{1}{3}\lambda w_5 + w_4 - w_5 \le 0 \\
\frac{1}{2}\lambda w_4 - w_1 + \frac{3}{2}w_4 \le 0 & \frac{1}{6}\lambda w_5 - w_2 + \frac{1}{2}w_5 \le 0 & \frac{1}{2}\lambda w_6 - w_4 + \frac{1}{2}w_6 \le 0 \\
\frac{1}{2}\lambda w_4 + w_1 - \frac{5}{2}w_4 \le 0 & \frac{1}{3}\lambda w_5 + w_2 - w_5 \le 0 & \frac{1}{2}\lambda w_6 + w_4 - \frac{3}{2}w_6 \le 0 \\
\frac{1}{2}\lambda w_5 - w_1 + w_5 \le 0 & \frac{1}{3}\lambda w_6 - w_2 + \frac{2}{3}w_6 \le 0 & \frac{1}{2}\lambda w_6 - w_4 + w_6 \le 0 \\
\frac{1}{2}\lambda w_5 + w_1 - 2w_5 \le 0 & \lambda w_6 + w_2 - 2w_6 \le 0 & \frac{1}{2}\lambda w_6 + w_4 - 2w_6 \le 0 \\
\frac{1}{2}\lambda w_6 - w_1 + \frac{3}{2}w_6 \le 0 & \frac{1}{6}\lambda w_5 - w_3 + \frac{1}{2}w_5 \le 0 & w_1 + w_2 + w_3 + w_4 + w_5 + w_6 = 1
\end{array}
$$

The model is implemented using CONOPT solver in GAMS software v. 24.1.2 on a machine with the following specifications: Core (TM) i3 1.70 GHz and 4 GB of RAM. The weights obtained for all sub-criteria after solving models for both criteria EC and OD are presented in Table 6.

3.1.3. Step 3: determining the score of each project

The experts are asked to score each project for every sub-criteria and criteria of project execution quality using the linguistic terms in Table 2. Table 7 illustrates the opinions of the six experts for the ten case study projects. The score of each project is then determined through summing up over the product of sub-criteria weights and the evaluated value for the project. Table 8 shows the results of these calculations.

3.1.4. Step 4: obtaining the final value of each project using FIS

The final score of each project is determined using FIS. We determine the relationships between the inputs (criteria) and the outputs (project scores) using fuzzy inference rules. Fig. 3 shows the questionnaire used to extract these fuzzy inference rules.

Note that as each criterion has three levels (low, medium and high)

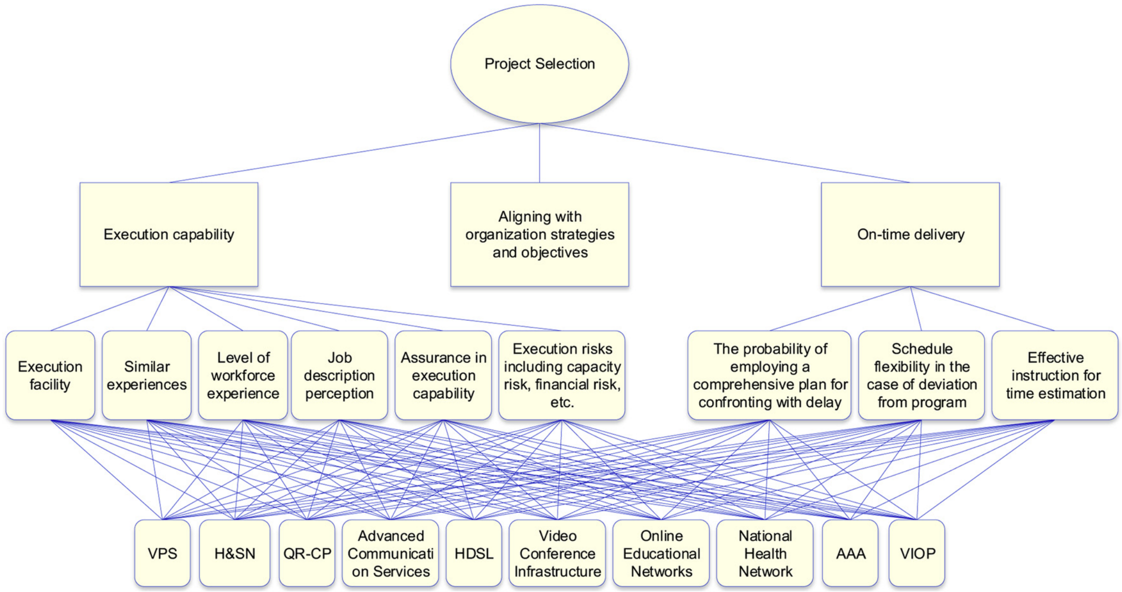


Fig. 2. The hierarchical structure between the goal, criteria, sub-criteria and projects.

Table 4
The pairwise comparison among execution capability sub-criteria.

	EC1	EC2	EC3	EC4	EC5	EC6
EC1	(1,1,1)	(2,5/2,3)	(3/2,2,5/2)	(3/2,2,5/2)	(1,3/2,2)	(3/2,2,5/2)
EC2	(1/3,2/5,1/2)	(1,1,1)	(1/2,2/3,1)	(1/2,2/3,1)	(1/2,2/3,1)	(2/3,1,2)
EC3	(2/5,1/2,2/3)	(1,3/2,2)	(1,1,1)	(1,1,1)	(1/2,2/3,1)	(1/2,1,3/2)
EC4	(2/5,1/2,2/3)	(1,3/2,2)	(1,1,1)	(1,1,1)	(1/2,2/3,1)	(1/2,1,3/2)
EC5	(1/2,2/3,1)	(1,3/2,2)	(1,3/2,2)	(1, 3/2, 2)	(1,1,1)	(1,3/2,2)
EC6	(2/5,1/2,2/3)	(1/2,1,3/2)	(2/3,1,2)	(2/3, 1, 2)	(1/2,2/3,1)	(1,1,1)

Table 5
The pairwise comparison among on-time delivery sub-criteria.

	OD1	OD2	OD3
OD1	(1,1,1)	(1,3/2,2)	(1,3/2,2)
OD2	(1/2,2/3,1)	(1,1,1)	(1/2,2/3,1)
OD3	(1/2,2/3,1)	(1,3/2,2)	(1,1,1)

Table 6
Sub-criteria weights.

Criteria	Sub-criteria	Weight
EC: Execution capability	EC1: Execution facility	0.341
	EC2: Similar experiences	0.030
	EC3: Level of workforce experience	0.161
	EC4: Job description perception	0.161
	EC5: Assurance in execution capability	0.251
	EC6: Execution risks including capacity risk, financial risk and etc.	0.056
OD: On-time delivery	OD1: The probability of employing a comprehensive plan for confronting with delay	0.465
	OD2: Schedule flexibility in the case of deviation from program	0.211
	OD3: Effective instruction for time estimation	0.324

and there are 3 criteria (EC, OD and A), 27 fuzzy inference rules are extracted. The rules are determined after the experts fill in the questionnaire.

We use the FIS Editor GUI toolbox in MATLAB 2012a to investigate the implication of the fuzzy inference rules. As there are three inputs to the system (EC, OD and A) and one output (score) we would need a four-dimensional plot, which is not possible. Thus, we generate three separate three-dimensional plots as shown in Fig. 4. Each plot shows the relationship between a pair of inputs and one output. The x and y axes represent the inputs to system (A, EC, or OD), while the z axis represents the system output (SCORE). The two input variables and the one output variable in all three figures vary between 0 and 1.

In Fig. 4(a), OD and A are the input variables and SCORE is the output variable, all varying between 0 and 1. The output surface in Fig. 4(a) shows that as the input values of OD and A increase, the output value of the SCORE increases. In other words, the output value of the SCORE is equally sensitive to OD and A.

In Fig. 4(b), the output surface shows that the input values A and EC only affect the SCORE output after a given threshold is reached by both these variables, with EC exhibiting a relatively lower threshold value.

In Fig. 4(c), the output surface exhibits a threshold effect of the input variables OD and EC on the SCORE output similar to the one described in Fig. 4(b) for A and EC. This effect arises for values of OD within the upper half of the domain on which it is defined. However, such threshold effect is reversed for values of OD located within the

Table 7
Average score of each project per each evaluation factor.

Criteria/sub-criteria	Project 1 VPS	Project 2 Hub-Spoke	Project 3 QR-Code Payment	Project 4 Advanced Communication Services	Project 5 HDSL	Project 6 Video Conference Infrastructure for Customers	Project 7 Online Educational Networks	Project 8 National Health Network	Project 9 AAA systems (Authentication, Accounting & Authorization)	Project 10 VIOP
EC1: Execution facility	0.6665	0.7915	0.5000	0.6665	0.8330	0.5833	0.7220	0.6663	0.5553	0.3890
EC2: Similar experiences	0.8332	0.6665	0.6247	0.5000	0.8330	0.6665	0.5000	0.5000	0.5000	0.5000
EC3: Level of workforce experience	0.7915	0.6665	0.4165	0.9165	0.6665	0.8330	0.1670	0.3890	0.5000	0.3890
EC4: Job description perception	0.7500	0.4583	0.2503	0.8330	0.5830	0.7498	0.7777	0.7777	0.6667	0.8330
EC5: Assurance in execution capability	0.8330	0.4583	0.3750	0.7500	0.6248	0.6250	0.3330	0.3333	0.5000	0.5000
EC6: Execution risks including capacity risk, financial risk and etc.	0.5000	0.8330	0.8330	0.5833	0.3335	0.3890	0.2780	0.8330	0.6665	0.6670
OD1: The probability of employing a comprehensive plan for confronting with delay	0.5418	0.6665	0.6248	0.4165	0.5000	0.7770	0.6667	0.9165	0.6250	0.4165
OD2: Schedule flexibility in the case of deviation from program	0.3748	0.8330	0.8330	0.5415	0.3750	0.7220	0.6110	0.8330	0.4165	0.6250
OD3: Effective instruction for time estimation	0.9165	0.6665	0.7915	0.5000	0.6665	0.6110	0.6110	0.9165	0.7500	0.8330
A: Alignment with organization strategies and objectives	0.5000	0.8330	0.6665	0.6670	0.5000	0.5000	0.8330	0.6665	0.6670	0.7777

lower half of its domain. In this case, the decrease of the SCORE value is symmetrically distributed within the domain of the input variable EC (Table 9).

3.2. Stage 2: optimal project portfolio selection

We construct a multi-objective zero-one mathematical model as per the previous section to select the optimal project portfolio. The model is implemented using CPLEX solver in GAMS software v. 24.1.2 on a machine with the following specifications: Core (TM) i3 1.70 GHz and 4 GB of RAM. The case study data used as input to the model (risk, income, cost and score for each project respectively) is shown in Table 10. The risk values, are extracted from Table 7. All criteria in the problem are desirable, except risk. Thus, the risk values in Table 7 are made desirable using the relation. The total available budget is 30 million dollars.

Zimmermann (1978) developed multi objective fuzzy linear programming, which can handle linguistic issues that arise in decision-making. We consider a symmetric fuzzy decision-making problem. Our proposed multi-objective model is reduced to a single objective model with the same weights by applying the method proposed by Zimmermann (1978). The resulting model is as follows:

$$\begin{aligned}
&Max\ \xi\\
&s.\ t.\\
&\xi \le \mu_{z_k^{min}}(x)\\
&\xi \le \mu_{z_r^{max}}(x)\\
&\mu_{Z_k^{min}}(x) = \begin{cases} 1 & , \quad z_k(x) > z_k^{positive} \\ 0 & , \quad z_k(x) < z_k^{negative} \\ f_{\mu_{Z_k^{min}}} = \dfrac{z_k^{positive} - z_k(x)}{z_k^{positive} - z_k^{negative}}, & z_k^{negative} \le z_k(x) \le z_k^{positive} \end{cases}\\
&\mu_{Z_l^{max}}(x) = \begin{cases} 1 & , \quad z_l(x) > z_l^{positive} \\ 0 & , \quad z_l(x) < z_l^{negative} \\ f_{Z_l^{max}} = \dfrac{z_l(x) - z_l^{negative}}{z_l^{positive} - z_l^{negative}}, & z_l^{negative} \le z_l(x) \le z_l^{positive} \end{cases}
\end{aligned} \tag{6}$$

The value of the objective function changes from lower bound to upper bound (from $z_k^{negative}$ to $z_k^{positive}$). In the above relation, $\mu_{z_k^{min}}(x)$ and $\mu_{z_r^{max}}(x)$ shows the membership functions for minimum and maximum objective functions, respectively. Hence, we have:

$$\begin{aligned}
&\mu_{Z^{benefit}}(x) = \frac{z^{benefit}}{10800000}\\
&\mu_{Z^{total\ value}}(x) = \frac{z^{total\ value}}{3.9594}\\
&\mu_{Z^{risk}}(x) = \frac{3.08325 - z^{risk}}{3.08325}
\end{aligned} \tag{7}$$

Therefore, the proposed model changes to the following:

$$Max\ \xi \tag{8}$$

$$s.\ t.$$

$$\frac{z^{benefit}}{10800000} \ge \xi \tag{9}$$

$$\mu_{Z^{total\ value}}(x) = \frac{z^{total\ value}}{3.9594} \ge \xi \tag{10}$$

$$\mu_{Z^{risk}}(x) = \frac{3.08325 - z^{risk}}{3.08325} \ge \xi \tag{11}$$

$$Max\ Z^{benefit} = \sum_i (I_i - c_i) \times x_i \tag{12}$$

Table 8
The score of each project per each criterion.

Criteria	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6	Project 7	Project 8	Project 9	Project 10
EC: Execution capability	0.73754	0.63265	0.43736	0.74486	0.68570	0.65237	0.51245	0.56035	0.55502	0.50724
OD: On-time delivery	0.62793	0.70163	0.72272	0.46993	0.52757	0.71161	0.63690	0.89888	0.62151	0.59544
A: Alignment with organization strategies and objectives	0.50000	0.83300	0.6665	0.66700	0.50000	0.50000	0.83300	0.66650	0.66700	0.77770

If to "EC" is	Low	And "OD" is	Low	And "A" is	Low		Then how should the final score of project be?	Low ☐	Low ☐	Low ☐
					Medium			Medium ☐	Medium ☐	Medium ☐
					High			High ☐	High ☐	High ☐
			Medium		Low			Low ☐	Low ☐	Low ☐
					Medium			Medium ☐	Medium ☐	Medium ☐
					High			High ☐	High ☐	High ☐
			High		Low			Low ☐	Low ☐	Low ☐
					Medium			Medium ☐	Medium ☐	Medium ☐
					High			High ☐	High ☐	High ☐
	Medium		Low		Low			Low ☐	Low ☐	Low ☐
					Medium			Medium ☐	Medium ☐	Medium ☐
					High			High ☐	High ☐	High ☐
			Medium		Low			Low ☐	Low ☐	Low ☐
					Medium			Medium ☐	Medium ☐	Medium ☐
					High			High ☐	High ☐	High ☐
			High		Low			Low ☐	Low ☐	Low ☐
					Medium			Medium ☐	Medium ☐	Medium ☐
					High			High ☐	High ☐	High ☐
	High		Low		Low			Low ☐	Low ☐	Low ☐
					Medium			Medium ☐	Medium ☐	Medium ☐
					High			High ☐	High ☐	High ☐
			Medium		Low			Low ☐	Low ☐	Low ☐
					Medium			Low ☐	Low ☐	Low ☐
					High			Medium ☐	Medium ☐	Medium ☐
			High		Low			High ☐	High ☐	High ☐
					Medium			Low ☐	Low ☐	Low ☐
					High			Medium ☐	Medium ☐	Medium ☐

Fig. 3. Questionnaire for extraction of fuzzy inference rules.

$$Max\ Z^{total\ value} = \sum_i SCR_i \times x_i \tag{13}$$

$$Min\ Z^{risk} = \sum_i r_i \times x_i \tag{14}$$

$$\sum_i c_i \times x_i \leq bg \tag{15}$$

The model is implemented using CPLEX solver in GAMS software v. 24.1.2 on a machine with the following specifications: Core (TM) i3 1.70 GHz and 4 GB of RAM. The results obtained show a profit of 9.85 million dollars, with a total project value of 3.902 and risk value of 1.751. The six projects chosen are: 1, 2, 3, 4, 8 and 10.

We now experiment by considering scenarios where the first (maximizing profit), second (maximizing total project value) and third (minimizing risk) objectives are considered separately. That is, we now have 3 single-objective zero-one mathematical models, as opposed to having a three-objective zero-one mathematical model.

For the first experiment, we run the model only caring about maximizing profit. The results obtained show a profit of 10.8 million dollars, with a total project value of 3.862 and risk value of 2.306. The six projects chosen are: 1, 2, 4, 7, 8 and 9. While the profit improves by 9%, the total project value deteriorates by 1% and the risk increases by 31%.

For the second experiment, where we only maximize total project value, the results obtained a profit of 9.55 million dollars, with a total project value of 3.959 and risk value of 2.195. The six projects chosen are: 1, 2, 4, 6, 8 and 10. While the total project value improves by 1.5% over the results yielded by the original model, the profit decreases by 3% and the risk increases by a massive 25%.

The third experiment, which only minimizes risk, does not yield any solutions as the model cannot minimize the risk without any constraint. Based on the results, we can see that increasing the weight of each objective does not reduce the optimal value of that objective function, and decreasing those weights does not improve the optimal values.

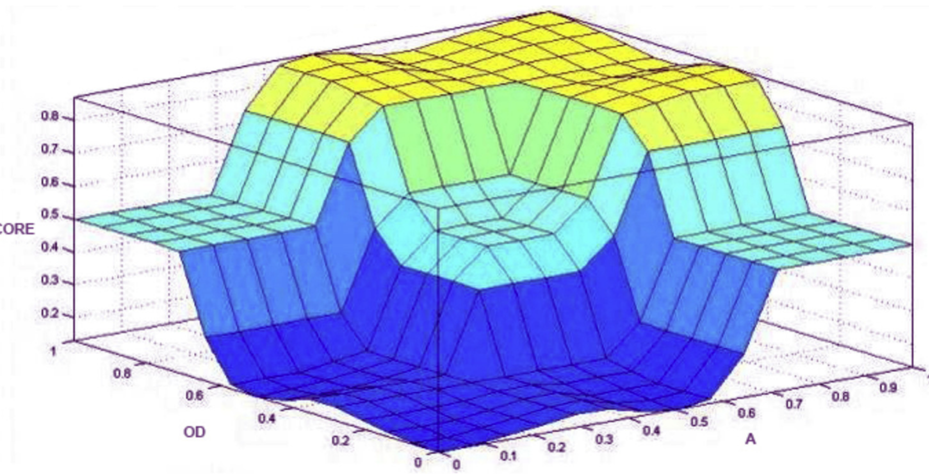
The results obtained from our experiments show that purely maximizing profit would significantly increase the profit obtained and incur a small amount of reduction in the project value, but would result in a large reduction of the risk value. Meanwhile, purely maximizing the total project value would improve the project value by a small margin and deteriorate the profit slightly, but would have a huge negative impact on the risk value. These results show that the risk value increases significantly when priority is put on other objective functions. From the model runs that yielded solutions, we can see that projects 1, 2 and 4 are always chosen. This indicates that these projects have good profitability, project value and risk value. In general, the results of this section can be summarized in Tables 11 and 12.

4. Sensitivity analysis

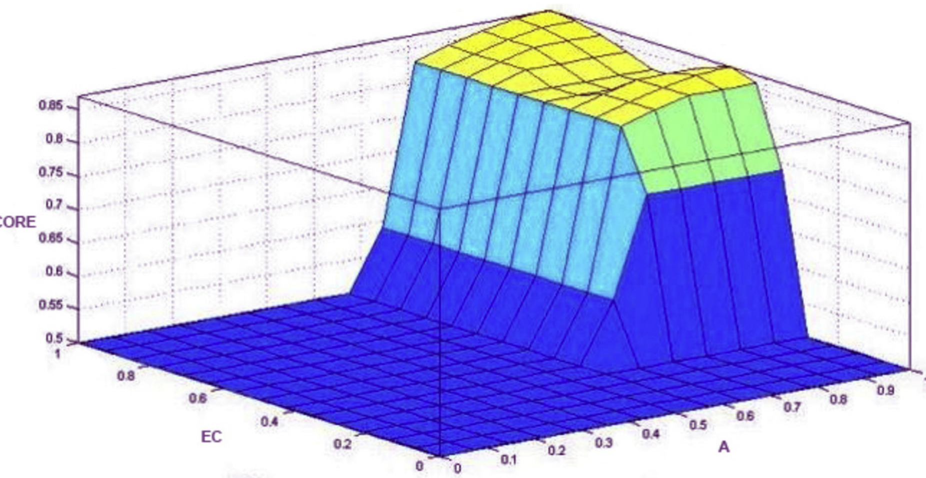
We investigate the efficacy of our proposed approach by performing sensitivity analysis on the solution obtained in the previous section. We considered the following three scenarios for sensitivity analysis:

4.1. Scenario 1: increasing budget

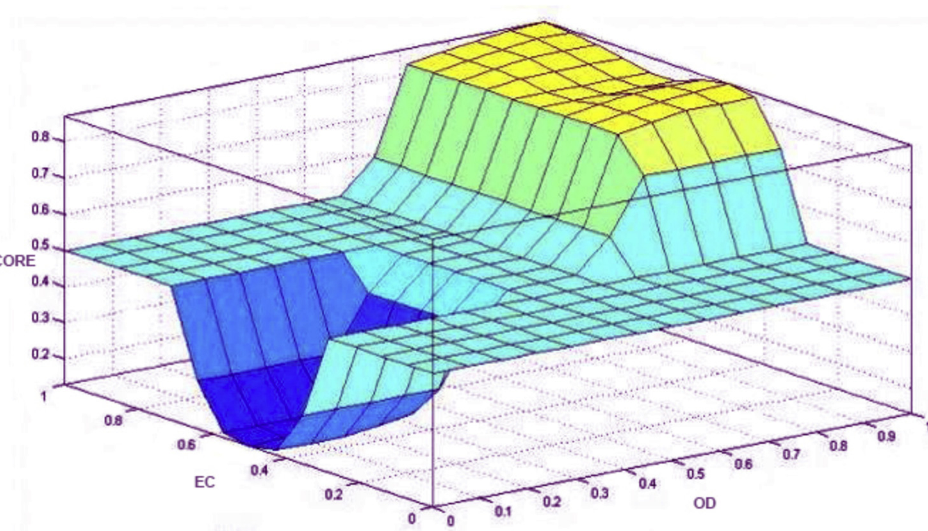
We were interested to see if the budget is increased (for example, by 5 million dollars), would the portfolio consist of projects 1, 2, 3, 4, 8, 9, and 10? Running our model with the budget increased to 35 million dollars yielded the same selected portfolio as expected by the experts. This new portfolio produces a profit of 11.35 million dollars, total project value of 4.474 and risk value of 2.085.



(a). Relationship between OD, A, and SCORE



(b). Relationship between EC, A, and SCORE



(c). Relationship between EC, OD, and SCORE

Fig. 4. Fuzzy inference rules.

4.2. Scenario 2: decreasing budget

We were interested to see if the budget is decreased (for example, by 5 million dollars), would the portfolio consist of projects 1, 2, 3, 4 and 8 or 1, 2, 4, 8 and 10. Running our model with the budget decreased to 25 million dollars resulted in the selected portfolio that includes projects 1, 2, 3, 4 and 8. This new portfolio produces a profit of 8.4 million dollars, total project value of 3.288 and risk value of 1.418.

Table 9
Final score of each project.

Project	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6	Project 7	Project 8	Project 9	Project 10
Final score	0.6488	0.7137	0.5831	0.6516	0.5481	0.6409	0.5862	0.6899	0.5715	0.6145

Table 10
Case study data.

Project	r_i	I_i	c_i	SCR_i
Project 1	0.5000	6,800,000	4,700,000	0.6488
Project 2	0.1670	5,200,000	3,700,000	0.7137
Project 3	0.1670	6,900,000	5,500,000	0.5831
Project 4	0.4168	6,00,0000	4,400,000	0.6516
Project 5	0.6665	7,200,000	6,200,000	0.5481
Project 6	0.6110	6,500,000	5,400,000	0.6409
Project 7	0.7220	7,400,000	5,100,000	0.5862
Project 8	0.1670	5,900,000	4,100,000	0.6899
Project 9	0.3335	7,500,000	6,000,000	0.5715
Project 10	0.3330	6,800,000	5,350,000	0.6145

Table 11
Objective function values for each scenario.

Scenario	Objective Function 1	Objective Function 2	Objective Function 3
All three objective functions are considered	9.85	3.902	1.751
Only the first objective function is considered	10.8	3.862	2.306
Only the second objective function is considered	9.55	3.959	2.195
Only the third objective function is considered	-	-	-

Table 12
Selected projects for each scenario.

Scenario	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6	Project 7	Project 8	Project 9	Project 10
All three objective functions are considered	√	√	√	√	-	-	-	√	-	√
Only the first objective function is considered	√	√	-	√	-	-	√	√	√	-
Only the second objective function is considered	√	√	-	√	-	√	-	√	-	√
Only the third objective function is considered	-	-	-	-	-	-	-	-	-	-

4.3. Scenario 3: changing the final score for project 9

We were interested to the effect of changing the final score of project 9 (for example, to 0.65). We expected that the change would result in project 9 replacing project 10 in the selected portfolio. Running our model with the change in place yielded a selected portfolio containing projects 1, 2, 3, 4, 8, and 9, which aligned with our expectations.

The results of the sensitivity analysis shows our proposed model is robust and not sensitive to small changes.

5. Conclusion

Project portfolio selection is one of the crucial decisions in organizations that greatly impacts profitability. In this study, we proposed a two-stage hybrid approach based on FAHP, FIS and mathematical programming to evaluate and select the optimal project portfolio under uncertainty in the IT industry. In the first stage, the value of each project from the strategic-operational perspective and its risks are measured using qualitative criteria by FAHP and FIS. In the second stage, a three-objective mathematical model, that maximized profit, maximizing the project value, and minimizing risk while also considering the budget constraint was developed to select the project portfolio.

We were able to use our approach and obtain a solution for a portfolio selection problem faced by a cyber-security company with over 6000 employees that needed to evaluate ten large cyber security projects, which covered a wide range of cyber security activities. We explored reducing the three-objective model to 3 single-objective models, where each model considered the first (maximizing profit), second (maximizing total project value) and third (minimizing risk) objectives separately. The results showed that focusing on one particular objective definitely improves the value of that objective, but would expectedly worsen the values associated with the other objectives. While focusing on profit does not seem to deteriorate project value and risk value by much, focusing on project value increases risk by a significant 25%. We also performed sensitivity analysis on the parameters of the problem according to three separate scenarios. The results indicates the proposed model is robust and not sensitive to small changes in the model parameters. These results altogether represent the effectiveness and efficacy of the model proposed in this study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Amindoust, A., Ahmed, S., Saghafinia, A., & Bahreininejad, A. (2012). Sustainable supplier selection: A ranking model based on fuzzy inference system. *Applied Soft Computing, 12*(6), 1668–1677.

Asosheh, A., Nalchigar, S., & Jamporazmey, M. (2010). Information technology project evaluation: An integrated data envelopment analysis and balanced scorecard approach. *Expert Systems with Applications, 37*(8), 5931–5938.

Badri, M. A., Davis, D., & Davis, D. (2001). A comprehensive 0–1 goal programming model for project selection. *International Journal of Project Management, 19*(4),

243–252.
Bermudez Peña, A., Lugo García, J. A., Pérez, P., & Yobanis, P. (2015). An adaptive-network-based fuzzy inference system for project evaluation. *Ingeniería y Universidad, 19*(2), 299–313.
Bosworth, B. P., & Triplett, J. E. (2000). *What's new about the new economy? IT, economic growth and productivity*. Processed, Brookings Institution.
Brynjolfsson, E., & Hitt, L. M. (2000). Beyond computation: Information technology, organizational transformation and business performance. *The Journal of Economic Perspectives, 14*(4), 23–48.
Cherkassky, V. (1998). *Fuzzy inference systems: A critical review. Computational intelligence: Soft computing and fuzzy-neuro integration with applications*. Berlin, Heidelberg: Springer177–197.
Dağdeviren, M., & Yüksel, İ. (2010). A fuzzy analytic network process (ANP) model for measurement of the sectoral competititon level (SCL). *Expert Systems with Applications, 37*(2), 1005–1014.
De Reyck, B., Grushka-Cockayne, Y., Lockett, M., Calderini, S. R., Moura, M., & Sloper, A. (2005). The impact of project portfolio management on information technology projects. *International Journal of Project Management, 23*(7), 524–537.
Ghapanchi, A. H., Jafarzadeh, M. H., & Khakbaz, M. H. (2008). An application of Data Envelopment Analysis (DEA) for ERP system selection: Case of a petrochemical company. *ICIS 2008 Proceedings, 77*.
Ghapanchi, A. H., Tavana, M., Khakbaz, M. H., & Low, G. (2012). A methodology for selecting portfolios of projects with interactions and under uncertainty. *International Journal of Project Management, 30*(7), 791–803.
Govindan, K., Rajendran, S., Sarkis, J., & Murugesan, P. (2015). Multi criteria decision making approaches for green supplier evaluation and selection: A literature review. *Journal of Cleaner Production, 98*, 66–83.
Han, C. H., Kim, J. K., Choi, S. H., & Kim, S. H. (1998). Determination of information system development priority using quality function development. *Computers & Industrial Engineering, 35*(1), 241–244.
Kahraman, C., Onar, S. C., & Oztaysi, B. (2015). Fuzzy multicriteria decision-making: A literature review. *International Journal of Computational Intelligence Systems, 8*(4), 637–666.
Kulak, O., Kahraman, C., Öztaysi, B., & Tanyas, M. (2005). Multi-attribute information technology project selection using fuzzy axiomatic design. *Journal of Enterprise Information Management, 18*(3), 275–288.
Lee, A. H., Chen, W. C., & Chang, C. J. (2008). A fuzzy AHP and BSC approach for evaluating performance of IT department in the manufacturing industry in Taiwan. *Expert Systems with Applications, 34*(1), 96–107.
Lee, J. W., & Kim, S. H. (2000). Using analytic network process and goal programming for interdependent information system project selection. *Computers & Operations Research, 27*(4), 367–382.
Lee, J. W., & Kim, S. H. (2001). An integrated approach for interdependent information system project selection. *International Journal of Project Management, 19*(2), 111–118.
Li, Y. P., Huang, G. H., & Chen, X. (2011). Planning regional energy system in association with greenhouse gas mitigation under uncertainty. *Applied Energy, 88*(3), 599–611.
Liang, C., & Li, Q. (2008). Enterprise information system project selection with regard to BOCR. *International Journal of Project Management, 26*(8), 810–820.
Mardani, A., Jusoh, A., & Zavadskas, E. K. (2015). Fuzzy multiple criteria decision-making techniques and applications—Two decades review from 1994 to 2014. *Expert Systems with Applications, 42*(8), 4126–4148.
Mina, H., Mirabedini, S. N., Kian, H., & Ghaderi, S. F. (2014). A new two stage integrated approach for green supplier selection. *Applied Mathematics in Engineering, Management and Technology, 1*(1) 1247-1126.
Oztaysi, B. (2014). A decision model for information technology selection using AHP integrated TOPSIS-Grey: The case of content management systems. *Knowledge-Based Systems, 70*, 44–54.
Oztaysi, B. (2015). A group decision making approach using interval type-2 fuzzy AHP for enterprise information systems project selection. *Journal of Multiple-Valued Logic & Soft Computing, 24*(5), 475–500.
Perez, F., & Gomez, T. (2016). Multiobjective project portfolio selection with fuzzy constraints. *Annals of Operations Research, 245*(1—2), 7–29.
Pramanik, D., Mondal, S. C., & Haldar, A. (2019). A framework for managing uncertainty in information system project selection: An intelligent fuzzy approach. *International Journal of Management Science and Engineering Management,* 1–9.
Rodríguez, A., Ortega, F., & Concepción, R. (2016). A method for the evaluation of risk in IT projects. *Expert Systems with Applications, 45*, 273–285.
Rodríguez, A., Ortega, F., & Concepción, R. (2017). An intuitionistic method for the selection of a risk management approach to information technology projects. *Information Sciences, 375*, 202–218.
Rosacker, K. M., & Olson, D. L. (2008). An empirical assessment of IT project selection and evaluation methods in state government. *Project Management Journal, 39*(1), 49–58.
Sagnak, M., & Kazancoglu, Y. (2019). IntegraFuzzy analytic network process and 0-1 goal programming technique for enterprise resource planning (Erp) software selection. *Ege Akademik Bakış Dergisi, 19*(1), 75–88.
Santhanam, R., & Kyparisis, G. J. (1996). A decision model for interdependent information system project selection. *European Journal of Operational Research, 89*(2), 380–399.
Santhanam, R., Muralidhar, K., & Schniederjans, M. (1989). A zero-one goal programming approach for information system project selection. *Omega, 17*(6), 583–593.
Schniederjans, M. J., & Wilson, R. L. (1991). Using the analytic hierarchy process and goal programming for information system project selection. *Information & Management, 20*(5), 333–342.
Sowlati, T., Paradi, J. C., & Suld, C. (2005). Information systems project prioritization using data envelopment analysis. *Mathematical and Computer Modelling, 41*(11), 1279–1298.
Stewart, R., & Mohamed, S. (2002). IT/IS projects selection using multi-criteria utility theory. *Logistics Information Management, 15*(4), 254–270.
Tavana, M., Azizi, F., Azizi, F., & Behzadian, M. (2013). A fuzzy inference system with application to player selection and team formation in multi-player sports. *Sport Management Review, 16*(1), 97–110.
Tavana, M., Keramatpour, M., Santos-Arteaga, F. J., & Ghorbaniane, E. (2015). A fuzzy hybrid project portfolio selection method using data envelopment analysis, TOPSIS and integer programming. *Expert Systems with Applications, 42*(22), 8432–8444.
Toloo, M., Nalchigar, S., & Sohrabi, B. (2018). Selecting most efficient information system projects in presence of user subjective opinions: A DEA approach. *Central European Journal of Operations Research, 26*(4), 1027–1051.
Uygun, Ö., Kaçamak, H., & Kahraman, Ü. A. (2015). An integrated DEMATEL and Fuzzy ANP techniques for evaluation and selection of outsourcing provider for a telecommunication company. *Computers & Industrial Engineering, 86*, 137–146.
Wu, H., Shen, J., Jones, J., Gao, X., Zheng, Y., & Krenn, H. Y. (2019). Using logic model and visualization to conduct portfolio evaluation. *Evaluation and Program Planning, 74*, 69–75.
Wu, Y., Zhang, B., Xu, C., & Li, L. (2018). Site selection decision framework using fuzzy ANP-VIKOR for large commercial rooftop PV system based on sustainability perspective. *Sustainable Cities and Society, 40*, 454–470.
Zandi, F., & Tavana, M. (2010). A multi-attribute group decision support system for information technology project selection. *International Journal of Business Information Systems, 6*(2), 179–199.
Zavadskas, E. K., Govindan, K., Antucheviciene, J., & Turskis, Z. (2016). Hybrid multiple criteria decision-making methods: A review of applications for sustainability issues. *Economic Research—Ekonomska istraživanja, 29*(1), 857–887.
Zimmermann, H. J. (1978). Fuzzy programming and linear programming with several objective functions. *Fuzzy Sets and Systems, 1*(1), 45–55.
Zou, A., Duan, S. X., & Deng, H. (2019). Multicriteria decision making for evaluating and selecting information systems projects: A sustainability perspective. *Sustainability, 11*(2), 347.