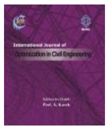
INTERNATIONAL JOURNAL OF OPTIMIZATION IN CIVIL ENGINEERING
Int. J. Optim. Civil Eng., 2019; 9(2):291-311



A MULTI-OBJECTIVE OPTIMIZATION MODEL FOR PROJECT PORTFOLIO SELECTION CONSIDERING AGGREGATE COMPLEXITY: A CASE STUDY

S.H. Iranmanesh[1], M. Shakhsi-Niaei[2*, †] and H. Rastegar[3]

[1] *School of Industrial Engineering, College of Engineering, University of Tehran, Tehran, Iran*

[2]*Department of Industrial Engineering, College of Engineering, Yazd University, Yazd, Iran*

[3]*School of Industrial Engineering, College of Engineering, University of Tehran, Tehran, Iran*

ABSTRACT

Existing project selection models do not consider the complexity of projects as a selection criterion, while their complexity may prolong the project duration and even result in its failure. In addition, existing models cannot formulate the aggregate complexity of the selected projects. The aggregated complexity is not always equal to summation of complexity of projects because of possible synergies or conflicts between them may increase or decrease the total complexity. In this paper, a model is proposed for measuring the aggregate complexity in the selection of project portfolios. A case study is presented to show the usefulness of the model and its applicability in practice. Moreover, several large-sized numerical examples have been tested showing the capability of the model to solve such problems in logical computational time.

Keywords: project management; mathematical programming; project selection; complexity; synergies; conflicts.

Received: 10 August 2018; Accepted: 22 November 2018

1. INTRODUCTION

The appearance of mega-projects and new project management systems have contributed towards a further augment in the uncertain and complex nature of projects. The classical

---

[*]Corresponding author: Department of Industrial Engineering, College of Engineering, Yazd University, Yazd, Iran

[†]E-mail address: m.niaei@yazd.ac.ir (M. Shakhsi-Niaei)

approach to project management considers three or at most five factors of a project to determine the situation of a project and to control it. These factors are cost, time and quality, as well as risk and scope in some project management methods [1]. Such factors appear to be sufficient to control the projects, but in recent years, many studies, surveys and standards have sought to extend the controlling factors. This is because project complexity may increase the risk and clutter the plans for the projects. Therefore, understanding the concept of project complexity and also determining the degree of complexity for a project are crucial issues when aiming for better control over it.

The primary aim of this paper is to present a comprehensive classification for project complexity and also the development of a new project complexity index. We aim to use this index as a criterion in the selection of candidate projects. It should be noted that the complexity degree of a project portfolio is not always equal to the summation of complexity degree of individual projects because there may be interactions between a set of selected projects [2]. Interactions between projects may decrease or even increase the complexity of the portfolio because of possible synergies or conflicts between the projects.

The remainder of this paper is organized as follows. Section 2 presents a concise literature review which is followed by the research methodology in Section 3. Section 4 describes how the complexity of the projects have been measured, and Section 5 is devoted to the proposed mathematical model and the calculation of aggregated complexity. The proposed model is implemented for a real case study and the corresponding results are discussed in Section 6 whilst the computational burden in large-sized problems is examined in Section 7. Finally, Section 8 concludes the paper.

2. LITERATURE REVIEW

In the following subsections, brief reviews of project portfolio selection and project complexity are provided.

2.1 Project portfolio selection

Project management has become a sophisticated tool for achieving competitive advantage and strategic goals [3]. Hence, it is needed to establish processes supporting and increasing project management effectiveness [4]. Project selection is a crucial decision especially in project-based organizations. It is always confronted by certain problems such as multiple and conflicting criteria to select suitable projects. Managers and decision makers must select some of the most attractive and profitable projects between the alternatives by considering different aspects of the project's efficiency [5]. In other words, the project selection process allocates limited resources to a set of projects considering the goals of the organization [6]. Since project selection is often characterized by multiple, conflicting and incommensurate criteria, it is a very difficult and complex decision-making process. In addition, there is a high level of uncertainty and incompleteness in project information, which makes this decision-making more complex [7]. Inappropriate decisions in project selection can lead to significant negative outcomes for the organization. First and foremost, there is an opportunity cost in terms of the resources that are wasted on unsuitable projects as the organization loses the benefits it could have gained if these resources had been spent on more suitable alternatives [8]. Since project selection has been a challenging issue for managers, many methods and criteria have been presented for selecting the best portfolio of projects [9].

Classical project selection methods concentrate on quantitative and financial tools such as discounted cash flow, net present value (NPV), return on investment (ROI) and payback period [10]. These approaches ignore many factors impacting the project selection and do not provide a useful transformative formula to combine all relevant criteria into a single decision-making model [11]. Therefore, multiple-criteria scoring and ranking methods have been widely employed to improve the project selection process. These methods are used to score projects with respect to each of the valuation objectives. Each objective is assigned a weight and each project is scored with respect to the objectives. There have been many criteria for selecting the projects. Table 1 shows a brief review of several project portfolio selection research and their considered criteria.

To the best of our knowledge, no study has considered complexity as a criterion in the project selection process.

Table 1: A brief review of the project portfolio selection researches

Category	Approach	Authors	Considered criteria
Benefit Measurement	Comparative models	Ghorbal-Blal [12]	Costs and benefits
	Scoring models	Nelson [13]	Technology, equipment, workload elasticity of capacity, cost/budget ratio and NPV
	AHP models	Anagnostopoulos and Petalas [14]	Economic, social and environmental benefits.
Mathematical Programming	Robust optimization	Hassanzadeh *et al.* [15]	Costs, contract values and schedules
	Constraint programming	Liu and Wang [16]	Summarized profit of the selected projects
	Linear programming models	Shakhsi-Niaei *et al.* [2]	Cost, methodology, personnel, scientific and technical capabilities
	Dynamic programming models	Kyparisis *et al.* [17]	Time-dependent NPV
	Fuzzy mathematical models	Khalili-Damghani *et al.* [18]	Net profit, costs, internal rate of return, unused resources
Cognitive Emulation	Decision-tree approaches	Heidenberger [19]	Cash, manpower, gross return
	Game-theory approaches	Grossman and Shapiro [20]	Technological competition

Simulation and Heuristics	Statistical approaches	Stahl and Harrell [21]	Cost/benefit ratio, technical merit, resource availability, likelihood of success, time period, need
	Decision process analysis	Schmidt and Freeland [22]	Learning, strategies formulation, goals, policies and project implementation
	Monte Carlo simulation	Shakhsi-Niaei *et al.* [23]	Cost, methodology, personnel, scientific and technical capabilities
	Conceptual mixed methods	Martinsuo *et al.* [24]	Uncertainty from organizational complexity, environment and single projects
Real Options Analysis	Active decision-making considering uncertainty	Luehrman [25]	NPV, expenditures, time to expiration, rate of return and variance of return
	Case-based reasoning	Li *et al.* [26]	Team and Manager experience, end year, duration, coding language, transactions, entities, project size, envergure, person hours
Ad-hoc Modelling	Unstructured and built-for-specific-purpose models	Hall and Nauda [27]	Additional expected annual profit

2.2 Project complexity

There is no single concept of complexity that can adequately capture our intuitive notion of what the term “project complexity” ought to mean. This is because there is no consensus on the meaning of project complexity and the origins of complexity [28].

Baccarini [29] classified the complexity of projects into organizational and technical aspects. Organizational complexity refers to human resources and management, while technical complexity refers to technological progress and new methods of carrying out a project. He noted uncertainty and risk of projects as the main sources of complexity and classified uncertainty and risk in goals, recourses, technology and effective elements in projects. Thus, the main factor added to the literature of complexity was risk.

Based on the studies of several researchers, i.e., Baccarini [29], Edmonds [30], and Bocquet *et al*. [31], we coin the following definition of project complexity: “The property of a project which makes it difficult to be understood, foreseen and kept under control, even when reasonably complete information about the project system is given.” According to this definition, the most important aspect of complexity is the unpredictability of the behavior of a project.

Numerous methods and models have been presented for measuring project complexity (Latva-Koivisto [32], Nassar and Hegab [33], Vidal *et al*. [1] & [34]). These models and methods can be classified into the following categories:

- Some models concentrate on one (or two) element(s) of the project like scheduling of the project or its sequencing problem [34].
- In the second group, the complexity of the project is fully dependent on its structure and as it changes, the complexity degree, which is calculated by the model, may be changed (e.g., Kaimann [35], Temperley [36], Nassar and Hegab [33]).
- The third group is more comprehensive as it concentrates on some important concepts like informational or systems-thinking-oriented measures. Information measures refer to the amount of time needed for transferring information through the whole project structure. In other words, the lower the speed of transferring information and disorder in a project, the higher the complexity of a project. Some models use entropic measurement of the complexity by Shannon or systems-thinking methods. Haas [37] described project complexity using a complicated system-thinking method which has some parameters including team composition and performance, cost and duration of project, political sensitivity and number of stakeholders.

The main limitation of the first group is that these models do not measure the whole complexity of the project. In other words, they just concentrate on one or two elements of the project like scheduling and do not show the complexity of the whole project.

The graph-based models, the second group, ignore the circumstances of the project. For example, two particular projects may have identical networks, but be performed in different environments, which makes their complexity especially different.

The third group, although more comprehensive and reliable, may have troublesome computational burden. Models like that of Shannon [38] or Haas [37] are difficult to calculate and analyze.

In order to resolve these problems, this paper presents a model which is tangible and easy-to-calculate and also represents the different resources of project complexity. The proposed model does not concentrate on the single elements of a project and instead takes into consideration the whole aspects of a project's effects on project complexity. The model is completely independent from the network graph of the projects. The proposed model does not have high computational complexity and can be easily used and understood by managers.

3. RESEARCH METHODOLOGY

Our research methodology consists of two main phases: 1) measuring the individual complexity of projects and 2) incorporating interactive complexities into the project portfolio selection problem. In the first phase, certain steps are taken in order to measure individual project complexities and in the second, the complexity indexes are incorporated in the project portfolio selection model. Fig. 1 presents the steps of our research methodology.

In the first step, the effects of the most important factors on project complexity are identified via a comprehensive study of several important factors. This includes the examination of, some related research, books and documents of several megaprojects. Also, the views of experts are considered in order to capture the factors which may have been ignored in previously published research. The output of this phase is the list of identified factors related to different complexity aspects.

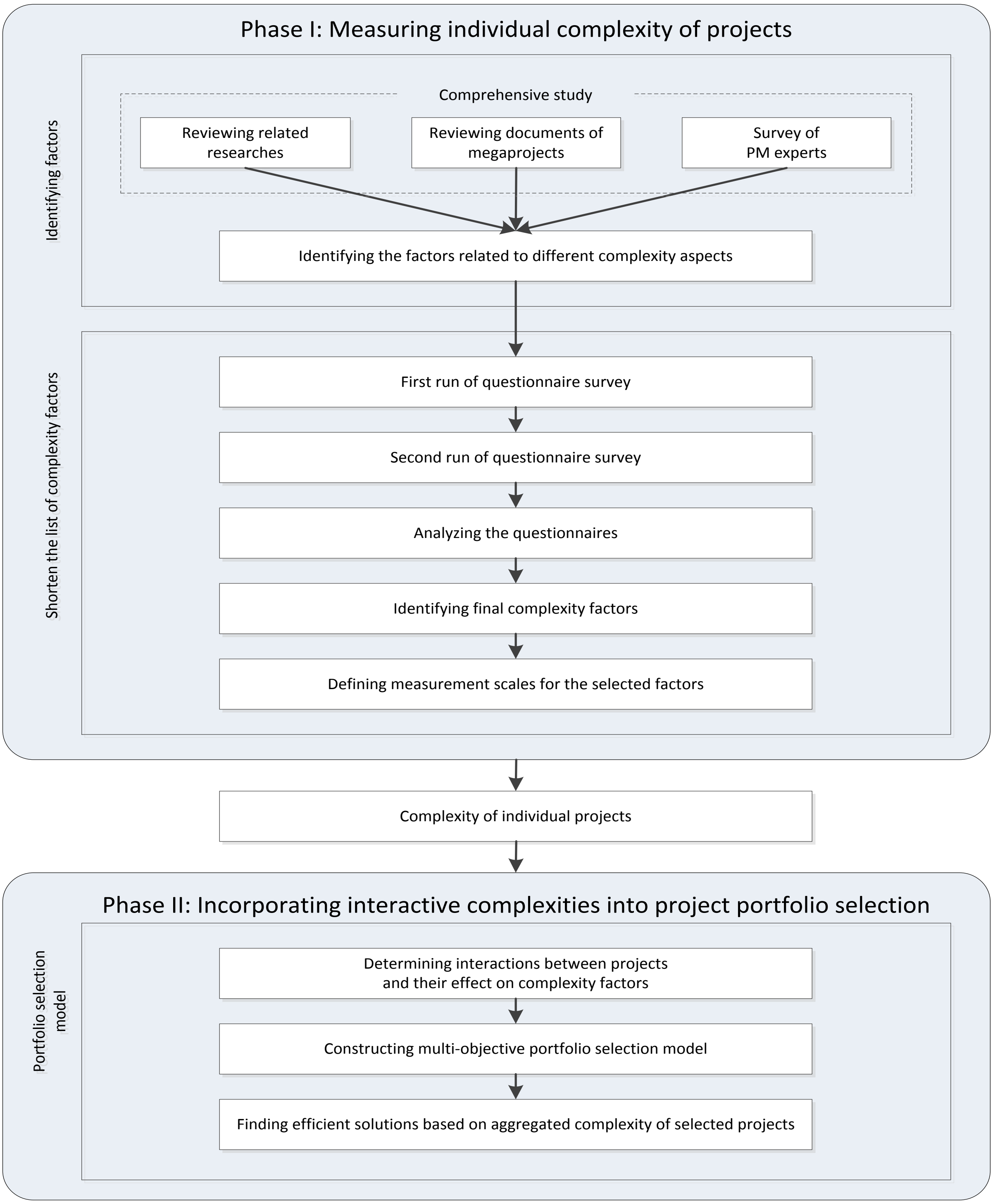


Figure 1. Research methodology

Then, the list of complexity factors is shortened and their weights determined. This step is taken through three sub-steps including two runs of questionnaire surveys and their analysis. Although the questionnaire methods and the chosen sample sizes are different in the literature, a group of 9 to 18 experts is recommended [39]. Okoli and Pawlowski [40] suggest that an expert classification should be done before sending the questionnaire. Skulmoski *et al*. [41] recommend participants' required competencies;

- being an expert in the related field, at least 10 years of experience,
- enough enthusiasm, capacity and time to participate,
- good communication skills.

In the second questionnaire survey, experts were asked to assign a score to those factors which are extracted from the first questionnaire. Prior to this, the detailed results of the first questionnaire were presented to them. Since this step is very important, some statistical experiments were carried out on the gathered data in order to improve the quality and the accuracy of the results. Cronbach's alpha was used to determine whether the scales were reliable and to drop the unusual scores. Moreover, principal component analysis (PCA) was employed to find possible principal components. Then, the weights of final complexity factors were determined based on the scores assigned by the experts.

After selection of final factors and determining their weights, measurement scales were designed for determining different levels in each selected factor. In order to do this, several meetings were held with five leading project management experts, who had at least 15 years of international experience. The chosen experts had good communication skills and extensive executive and academic experience in the project management field. After determining the measurement scale for each factor, it is possible to calculate the complexity of projects using the factors, weights and measurement scales.

The last phase is to construct a project portfolio selection model using aggregated complexity, taking into account possible interactions between the projects. The proposed project portfolio selection model has two objectives, i.e. maximizing the total net present value and minimizing the aggregated complexity of the selected projects. The model considers the possible interactions between a pair of projects if both are selected. Special constraints can be added to the model, for example segmentation, policy and logical constraints.

As mentioned before, the complexity of the project portfolio is not requisitely equal to the summation of complexity of individual projects owing to the possible existence of positive or negative interactions between the selected projects. Therefore, interactions between projects are also accounted for in the proposed model.

The results of the model are some efficient solutions which suggest the optimal combination of projects considering possible interactions between the projects and also their individual complexities.

4. MEASURING THE COMPLEXITY OF THE PROJECTS

In relation to the definition of project complexity presented in Section 2-2, this is something more than uncertainty or having multiple elements because the complexity has several factors and aspects which can affect the project. We classified the complexity resources into structural and environmental components. Structural complexity is related to the mechanism of a project and can be further classified into multiplicity, variety and inter-dependency between project elements. On the other hand, environmental complexity refers to the surrounding factors of a project like risks and uncertainty. Fig. 2 shows the proposed classification for the components of the project complexity.

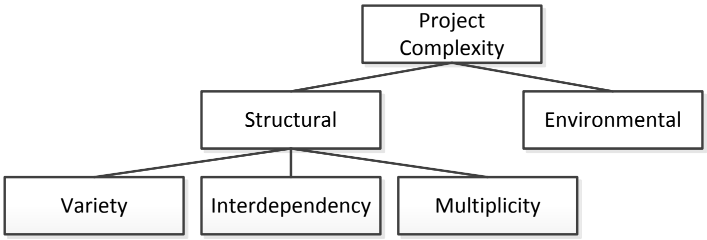


Figure 2. Components of project complexity

After classifying the components of project complexity, a procedure which contains the following steps is implemented in order to calculate the complexity index for each individual project.

It is pertinent to note that the factors identified here cannot be generalized to all countries and industries because each has its own features and specifications. However, they can be easily identified by implementing the same methodology in the respective country/industry.

4.1 Determining the most important factors and their weights

This step was taken via the following sub-steps.

4.1.1 Identifying complexity factors

After reviewing the relevant literature, a comprehensive list including 60 factors was extracted, as shown in the second column of Table 2. It contains 49 structural and 11 environmental factors. Among the structural factors, 18 are related to multiplicity, 12 to variety and 19 to interdependency. However, the data gathering process would be overwhelming, and so this calls for a shortening of the list which is achieved via two runs of questionnaire surveys.

4.1.2 Identifying the factors with significant effect on the complexity – first run

Nine academic and nine experienced project managers participated in this survey: nine males and nine females. The experts were asked to study the 60 factors and select the 10 most important factors by assigning a number between 0 and 100 to each selected factor, which is consequently treated as its weight. Moreover, each expert was allowed to add some additional factors to the list.

The questionnaires were carefully analyzed using the IBM SPSS Statistics Software. In this run of the survey, the factors which cover 70% of cumulative normalized weights were extracted and used as the input of the second run. This decision is made based on a generalization of the Pareto principle which states that, for many applications, approximately 80% of the effects emerge from 20% of the causes [42]. In this regard, 19 factors that cover 70% of the cumulative normalized weight of experts' scores are selected, as shown in bold in the last column of Table 2.

Table 2: Selecting the most important factors through the first run of the survey

Row	Factor	Complexity aspect and sub-aspect		Sum of assigned weights	Cumulative normalized weight
1	Political restrictions	Env	-	75	**0.078947**
2	Number of decision makers	Str	Mult	69	**0.15157**
3	Number of activities	Str	Mult	57	**0.21158**
4	Number of goals of project	Str	Mult	45	**0.25900**
5	Number of components	Str	Mult	43	**0.30421**
6	Variety of components	Str	Var	38	**0.34421**
7	Interdependency between activities	Str	Int	38	**0.38421**
8	New sudden programmers and laws effective in project	Env	-	35	**0.42105**
9	Interdependencies with environment	Env	-	32	**0.45473**
10	Technological changes	Env	-	29	**0.45826**
11	Interdependencies with other projects of organization	Str	Int	27	**0.51368**
12	Interdependencies between phases of the project	Str	Int	25	**0.54000**
13	Number of deliverables	Str	Mult	24	**0.56526**
14	Inflation in materials used in project	Env	-	24	**0.59052**
15	Variety of hierarchical levels in organization	Str	Var	22	**0.61368**
16	Variety of needed skills	Str	Var	22	**0.63684**
17	Number of suppliers	Str	Mult	20	**0.65789**
18	Number of hierarchical levels in organization	Str	Mult	20	**0.67894**
19	Feedback loops in project graph	Str	Int	20	**0.70000**
20	Interdependencies with suppliers	Str	Int	20	0.72105
21	Largeness of investment	Str	Mult	18	0.74000
22	Dependencies between activities of the project	Str	Int	18	0.75894
23	Number of stakeholders	Str	Mult	16	0.77578
24	Number of groups in project	Str	Mult	16	0.79263
25	Influence of beneficiaries	Env	-	16	0.80947
26	Number of staff	Str	Mult	15	0.82526
27	Number of managers	Str	Mult	15	0.84105
28	Variety of interests of stakeholders	Str	Var	13	0.85473
29	Interdependencies between goals	Str	Int	12	0.86736
30	Number of connectors	Str	Mult	10	0.87789
31	Number of departments involved	Str	Mult	10	0.88842
32	Quantity of resources	Str	Mult	10	0.89889
33	Access to human and resources	Str	Int	10	0.90947
34	Protests and political unrests	Env	-	10	0.92000
35	Number of investors	Str	Mult	9	0.92947
36	Variety of financial resources	Str	Var	9	0.93849
37	Projects should share with them	Str	Mult	8	0.94736

Row	Factor	Complexity aspect and sub-aspect		Sum of assigned weights	Cumulative normalized weight
38	Variety of skills needed	Str	Var	8	0.95578
39	Variety of organizational dependency	Str	Var	8	0.96421
40	Relations between stakeholders	Str	Int	8	0.97263
41	Local laws and regulations	Env	-	8	0.98105
42	Variety of information systems	Str	Var	7	0.98842
43	Decisions of local government	Env	-	6	0.99473
44	Number of information systems	Str	Mult	5	1
45	Duration of the project	Str	Mult	0	1
46	Process interdependencies	Str	Int	0	1
47	Variety of stakeholder’s status	Str	Var	0	1
48	Variety of project management tools and methods used	Str	Var	0	1
49	Variety of management ranks	Str	Var	0	1
50	Dependencies between sites	Str	Int	0	1
51	Team cooperation and communication between staff	Str	Int	0	1
52	Dependencies with permanent organization	Str	Int	0	1
53	Relations between staff	Str	Int	0	1
54	Dependencies between staff	Str	Int	0	1
55	Dependencies with local weather	Env	-	0	1
56	Cooperation between managers	Str	Int	0	1
57	Cultural configuration and variety	Env	-	0	1
58	Competitors	Env	-	0	1
59	Noise in input data	Env	-	0	1
60	Location of stakeholders	Str	Int	0	1

4.1.3 The second survey

In the previous step, 19 factors were extracted which cover 70% of cumulative normalized weights of experts’ scores. Thereafter the second questionnaire was designed and 18 experts were asked to assign a score of between 0 and 100 to those 19 factors. Subsequently, 10 factors which had the highest scores were selected. Table 3 shows the final 10 factors and also their weights. Of these 10 factors, four are environmental and six are structural.

Table 3: Final selected factors and their weights

Row	Factor	Complexity aspect and sub-aspect		Sum of assigned weights	Cumulative normalized weight
1	Political restrictions	Env	-	65.66	0.124
2	Inflation in materials used in project	Env	-	59.38	0.112
3	Number of decision makers	Str	Mult	57.17	0.108
4	New sudden regulations and laws effective in project	Env	-	54.71	0.103

Row	Factor	Complexity aspect and sub-aspect		Sum of assigned weights	Cumulative normalized weight
5	Number of components	Str	Mult	52.14	0.098
6	Interdependency between activities	Str	Int	50.83	0.096
7	Number of activities	Str	Mult	50	0.094
8	Interdependencies between phases of the project	Str	Int	47.51	0.09
9	Technological changes	Env	-	46.28	0.087
10	Variety of needed skills	Str	Var	46.25	0.087

4.2 Defining measurement scales for the selected factors

Table 4 shows the defined scales for each complexity factor which have been determined by the experts.

Table 4: Description of scales defined for the complexity factors

Factor	Scales		
	0	0.5	1
Political restriction	It is not very likely	It is quite likely	It exists now and is likely to continue
Inflation	Lower than 5%	Between 5% and 10%	Greater than 10%
Number of decision makers	Not greater than three	Four or five	More than five
New regulations and laws affecting the project	It is unlikely	It is rather likely	It is extremely likely
Number of components	Less than 50	Between 50 and 200	More than 200
Interdependency between activities	There is no or very low interdependencies	Partial dependencies	Total interdependencies
Number of main activities	Less than 100	Between 100 and 200	More than 200
Interdependencies between phases	There is no or very low interdependencies	Partial dependencies	Total interdependencies
Technological changes	It is unlikely	It is rather likely	It is extremely likely
Variety of skills needed	Less than 10 skills	Between 10 and 15 skills	More than 15 skills

The calculation of the aggregated complexity is described in the next section; this is where the combination of selected projects can affect the total complexity of the project portfolio.

5. PROPOSED PROJECT SELECTION MODEL INCLUDING AGGREGATED COMPLEXITY

The notation used in our project portfolio selection model is as follows; parameters are shown in capitals.

Indexes:
i,*k* Candidate projects.
j Complexity factors.
Parameters:
W_j Weight of factor *j*.
NPV_i Net present value of project *i*.
D_{ikj} Positive or negative interactive effect on factor *j* if projects *i* and *k* are both selected.
C_i Budget needed for project *i*.
S_{ij} Score of project *i* in factor *j*.
B Total budget of organization.
*BR*Minimum preferred rate of budget consumption.
Variables:
y_i Binary variable representing selection/not selection of project *i*.
yy_{ik} Binary variable showing selection/not selection of projects *i* and *k* simultaneously.
z_1 Sum of net present value of selected projects.
z_2 Aggregated complexity of selected projects.
The primary portfolio selection model is formulated as follows.

$$Max\ z_1 = \sum_{i=1}^{n} y_i\ NPV_i, \tag{1}$$
$$Min\ z_2 = \sum_{i=1}^{n}\sum_{j=1}^{m} W_j\ S_{ij}\ y_i + \sum_{i=1}^{n}\sum_{k\neq i}^{n}\sum_{j=1}^{m} W_j\ D_{ikj}\ y_i y_k, \tag{2}$$
Subject to:
$$\sum_{i=1}^{n} y_i\ C_i \ \le B, \tag{3}$$
$$\sum_{i=1}^{n} y_i\ C_i \ \ge B.\ BR, \tag{4}$$
$$y_i, y_k \in [0, 1]. \tag{5}$$

Equation (1) maximizes total NPV and Equation (2) minimizes the complexity of the portfolio. Equation (3) restricts the expenditures to the governmental/organizational budget. In the considered case study, there was a tacit rule that the organization ought to spend at least a specific portion of its current budget in order to receive the same amount of budget in the next year from the related ministry. In this way, Equation (4) enforces that *BR* percent of the budget should be spent for the projects. The multiplication of y_i and y_k, as two variables, makes the model non-linear, which may result in non-optimal final solutions. Thus, the model is mapped into a linear model via defining a new variable yy_{ik}, which is equal to 1 if both projects *i* and *k* are selected, 0 otherwise. In addition, equations (6) to (8) should be added to the model in order to formulate the relations between yy_{ik} , y_i and y_k variables.

$$yy_{ik} \le\ y_i\ , \forall i, k, \tag{6}$$
$$yy_{ik} \le\ y_k\ , \forall i, k, \tag{7}$$

$$yy_{ik} \geq y_i + y_k - 1, \forall i, k \tag{8}$$

It should be noted that if there are interactive effects between triple or even larger subsets of projects, the positive or negative interactive effects can be formulated by adding one or more indices to parameter D_{ikj}. Moreover, the Equations (6–8) should be extended in order to cover the new index.

6. CASE STUDY

The case study presented here shows the application of the proposed model to a municipal-related organization. The considered organization provides several municipal services in the city of Tehran and performs three types of projects, entitled A, B and C, based on the projects required by Tehran municipality. The projects of the organization are scattered over 22 municipal districts in Tehran, which vary in the number of projects required. Fig. 3 illustrates the distribution of 40 candidate projects over the map of Tehran.

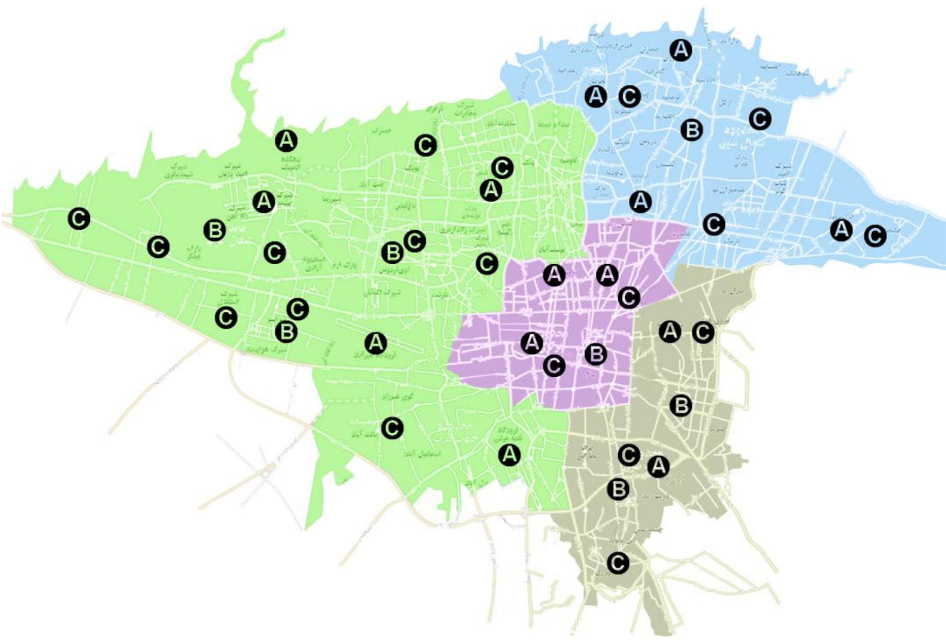


Figure 3. Distribution of candidate projects and their types

The organization has an annual budget of 1842 (×1000 USD), which is considered in Equation (9).

$$\sum_{i=1}^{n} y_i C_i \leq 6000 \tag{9}$$

Based on the experts' comments, the total A-type projects should not be greater than 0.1

of all the selected projects. Also, more than 0.3 of projects should not be from type B and, finally, the C-type projects should not be more than 0.6 of all those selected. Thus, based on these limitations, constraints (10), (11) and (12) are added to the model.

$$y_2+y_7+y_9+y_{12}+y_{13}+y_{14}+y_{17}+y_{22}+y_{23}+y_{26}+y_{28}+y_{37}+y_{38}+y_{39}\le 0.1\sum_{i=1}^{n} y_i, \quad (10)$$

$$y_5+y_8+y_{15}+y_{19}+y_{29}+y_{34}+y_{40}\le 0.3\sum_{i=1}^{n} y_i, \quad (11)$$

$$y_1+y_3+y_4+y_6+y_{10}+y_{11}+y_{16}+y_{18}+y_{20}+y_{21}+y_{24}+y_{25}+y_{27}+y_{30}+y_{31}+y_{32}+y_{33}+y_{35}+y_{36}\le 0.6\sum_{i=1}^{n} y_i. \quad (12)$$

The organization should spend at least 0.8 of its allocated budget. Therefore, constraint (13) is added to the model.

$$\sum_{i=1}^{n} y_i\, C_i \ge 4800 \quad (13)$$

Other information about the projects is shown in Table 5.

Table 5: Data set of alternative projects in the case study

Project	Segment	Cost (×1000 USD)	NPV (×1000 USD)
Project 1	C	120.97	35.31
Project 2	A	11.21	3.99
Project 3	C	124.19	39.91
Project 4	C	130.03	53.42
Project 5	B	46.52	4.30
Project 6	C	123.89	37.46
Project 7	A	11.97	3.68
Project 8	B	43.60	13.82
Project 9	A	11.82	4.61
Project 10	C	129.87	53.42
Project 11	C	114.06	3.68
Project 12	A	13.05	3.38
Project 13	A	12.59	5.53
Project 14	A	12.43	6.14
Project 15	B	51.12	7.37
Project 16	C	132.02	37.15
Project 17	A	12.13	4.30
Project 18	C	120.05	42.68
Project 19	B	44.37	11.97
Project 20	C	113.45	26.40
Project 21	C	112.07	32.85
Project 22	A	13.66	6.45
Project 23	A	13.20	4.91
Project 24	C	122.81	18.42
Project 25	C	116.52	26.40

Project 26	A	12.59	4.61
Project 27	C	120.05	3.07
Project 28	A	11.97	3.68
Project 29	B	46.05	20.88
Project 30	C	123.43	23.33
Project 31	C	130.33	29.17
Project 32	C	122.35	4.61
Project 33	C	109.46	23.64
Project 34	B	41.76	11.97
Project 35	C	124.65	11.05
Project 36	C	131.41	6.75
Project 37	A	12.59	4.91
Project 38	A	12.13	3.38
Project 39	A	12.43	4.30
Project 40	B	46.52	10.44

Since there are 40 alternative projects and 10 complexity factors, 400 S_{ij} have been evaluated. The next step is to determine the possible interactions between pair of projects (d_{ikj}) . Eight pair of projects with interactive effects were detected as: $d_{3,6,10}$= 0.3, $d_{6,11,3}$= -0.2, $d_{7,9,3}$= 0.3, $d_{10,18,3}$= -0.4, $d_{13,17,10}$= 0.3, $d_{16,24,10}$= - 0.3, $d_{28,39,10}$ = 0.3 and $d_{31,36,3}$= 0.2. For example, by performing projects 3 and 6 simultaneously, some issues related to the environment of the project and local government may arise which need extra skills. This negative interaction, increase in complexity, is evaluated by $d_{3,6,10}$= 0.3. As another example, if project 6 is performed, a part of the supervisions will be unnecessary for project 11. Hence, the supervision team of project 11 will be shrunk. This positive interaction is evaluated with $d_{6,11,3}$= -0.2.

The proposed mathematical model has been formulated as a bi-objective mixed-integer-linear-programming model. Among all the approaches for solving multi-objective problems, ε-constrained method seems to be the most common method [43]. By altering one parameter in the right-hand side of the constrained objective functions, several efficient solutions of the problem are obtained. A famous version of ε-constrained method is augmented ε-constrained method (AUGMECON) presented by Mavrotas [44], who provides further information about the AUGMECON method.

The final result of the model is a frontier of solutions called Pareto-optimal set. Since managers have different levels of risk taking, the convenient portfolio can be widely varied for different managers. In the proposed model, the manager can increase the probability of having higher returns by taking more level of complexity (risk) and vice versa. Based on different levels of complexity, the efficient frontier is classified and efficient solutions are obtained. In an efficient solution, it is impossible to make any better objective function value without making at least another objective function worse. Fig. 4 shows a sample efficient frontier for a numerical example extracted from Mavrotas [44], including points A’, B’, C’, D’ and E’.

A pay-off table is determined in the case study by calculating the range that objective functions can vary. In this way, z_1 is optimised (z_1^*) and the value of z_2 is calculated based on this solution, which is not requisitely optimised. Then, z_2 is optimized (z_2^*) and the related value of z_1 is then calculated. The resulting payoff is shown in Table 6.

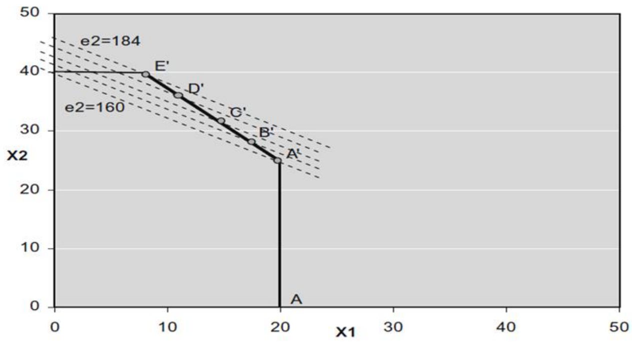


Figure 4. A sample efficient frontier (Mavrotas, 2009)

Table 6: Pay-off table in the case study

Objective function which is optimized	z_1	z_2
z_1	1716*	-10.511
z_2	1334	-9.395*

*: optimized value

The next step is to create new objective function and constraints based on the determined pay-off table and the altering parameter, α. The new model is:

$$Max\ z_2 = -\left(\sum_{i=1}^{n} \sum_{j=1}^{m} W_j\, S_{ij}\, y_i + \sum_{i=1}^{n} \sum_{k \neq i}^{n} \sum_{j=1}^{m} W_j\, d_{ikj}\, yy_{ik} \right).$$
$$Subject\ to:$$
$$\sum_{i=1}^{n} y_i\ NPV_i \geq 1334 + \alpha\,(1716 - 1334). \tag{14}$$
$$\text{In addition to equations } (6-13)$$
$$y_i\ and\ yy_{ik} \in \{0,1\}.$$

By solving the model with different α values from 0 to 1, the frontier of efficient solutions will be estimated. Table 7 shows the efficient solutions which are plotted in Fig. 5.

Table 7: Efficient solutions for objective functions

Α	z_1	z_2
0	1334	-9.395
0.1	1422	-9.407
0.2	1422	-9.407
0.3	1472	-9.465
0.4	1494	-9.492
0.5	1527	-9.537
0.6	1571	-9.588
0.7	1602	-9.730
0.8	1641	-9.779
0.9	1678	-9.989
1	1716	-10.511

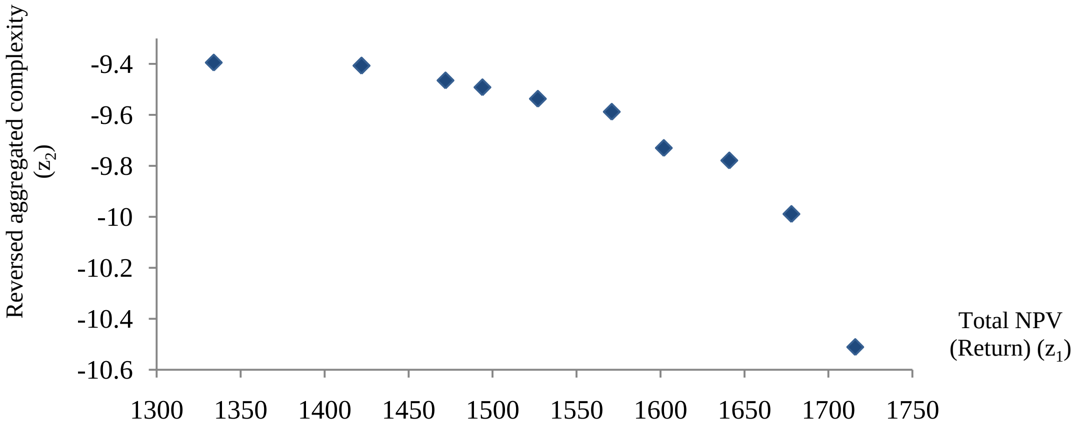


Figure 5. Efficient solutions

Any efficient solution can be selected as the final solution according to the preferences of the decision makers. For example, if a decision maker considers the same priority for two objective functions, α is considered equal to 0.5 and projects 1–5, 8, 10, 12, 15, 18–21, 25 and 29–34 are selected as the portfolio of projects with total NPV of 1527. Based on different values of α, maximum changes in NPV and complexity objective functions are 382 and 1.116 units, respectively.

The first point on the efficient frontier (1330, -9.4) has less complexity degree, but also the least return. On the other hand, the last point (1730, -10.6) has more complexity and also a higher potential return.

7. COMPUTATIONAL COMPLEXITY

In real-world applications, public project-based organizations are faced with much more projects in comparison to the size of our case study. For example, some state organizations may have to choose from a portfolio of between 500 and 1000 candidate projects. Thus, the main question here is whether the proposed model can be efficiently solved when faced with such large dimensions.

In order to analyze the model in this respect, several numerical examples are randomly generated and solved with the aforementioned model. In this way, problems with 100, 200, 500, 1000 and 5000 projects are solved by GAMS 24.1.2 on a personal computer with a 2 GHz Pentium® Dual-Core CPU. Table 8 shows the computational time required for each problem. It is clear that the time needed to solve these problems, even with high dimensions, is logical. For this reason, there is no need to implement any approximate approaches to solve the real-sized problems. Fig. 6 shows the relation between the number of projects and the required computational time.

Table 8: Computational time for different problem sizes

Number of projects	Computational time (minutes)
100	3.561
200	6.385
500	10.875
1000	14.789
2000	16.125
3000	17.565
4000	19.356
5000	20.470

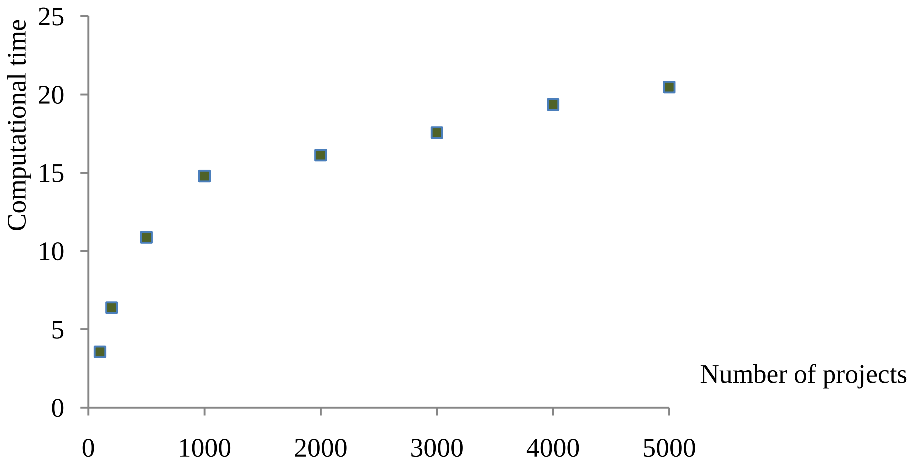


Figure 6. Relation between number of projects and computational time

8. CONCLUSION

In this paper, a comprehensive approach is proposed for project portfolio selection, which covers two main phases, i.e., measuring the individual complexity of projects and incorporating interactive complexities into the project portfolio selection model. To do so, a definition of complexity is first presented based on various existing research. Moreover, the possible sources of project complexity are determined – and the most important factors are identified by conducting two runs of a survey. A model is proposed for considering the aggregated complexity of the selected projects. The model can show the sources of complexity in projects and help decision makers to find and control the origins of the complexity in the projects. In order to show the usefulness of the model and its applicability in practice, a case study is presented.

The results show that the complexity degree of a portfolio may be different from the sum of complexity degrees of individual projects because of possible interactions between them. In order to evaluate the capability of the model to solve real-world large-sized problems, some numerical examples are randomly generated and tested; the results prove that the proposed model can be implemented even with 5000 candidate projects. There are also several ways to extend this work. First, an expert system can be used in order to show the complexity and its sources in different projects. The expert system may calculate the complexity degree of projects more accurately and help managers to make decisions more systematically.

Acknowledgement: The authors are grateful to the anonymous referees for their valuable comments, which helped improve the quality of our paper and its presentation. Moreover, financial support from the Iran National Science Foundation (INSF) by grant #93021446 is acknowledged.

REFERENCES

1. Vidal L, Marle F, Bocquet JC. Using a delphi process and the AHP to evaluate the complexity of projects, *Expert Syst Applicat* 2011; **38**(11): 5388-5405.
2. Shakhsi-Niaei M, Shiripour M, Shakouri H, Iranmanesh SH. Application of genetic and differential evolution algorithms on selecting portfolios of projects with consideration of interactions and budgetary segmentation, *Int J Operational Res* 2014; **22**(1): 106-28.
3. Jovanovic P, Obradovic V, Petrovic D, Mihic M, Jovanovic A. Cross-cultural aspects of project management: Serbia goes to Iraq for Jordan project, *Int J Indust Eng* 2009; **16**(4): 318-30.
4. Spalek S. Establishing a conceptual model for assessing project management maturity in industrial companies, *Int J Indust Eng* 2015; **22**(2): 301-13.
5. Mavrotas G, Diakoulaki D, Kourentzis A. Selection among ranked projects under segmentation, policy and logical constraints, *European J Operat Res* 2008; **187**(1): 177-92.
6. Medaglia AL, Graves SB, Ringuest JL. A multi-objective evolutionary approach for linearly constrained project selection under uncertainty, *European J Operat Res* 2007; **179**(3): 869-94.
7. Wang J, Xu Y, Li Z. Research on project selection system of reevaluation of engineering design project bidding, *Int J Project Manage* 2009; **27**(6): 584-99.
8. Martino JP. *Research and Development Project Selection*, Wiley Series in Engineering & Technology Management, USA, 1995.
9. Iamratanakul S, Patanakul P, Milosevic D. Project portfolio selection: From past to present, *Proceedings of 4th IEEE International Conference on Management of Innovation and Technology*, Bangkok, Thailand, 2008, pp. 287-292.
10. Liberatore MJ. An extension of the analytic hierarchy process for industrial R&D project selection and resource allocation, *IEEE Transact Eng Manage* 1987; **34**(1): 12-18.
11. Brewer PC, Gation AW, Reeve JM. *Managing Uncertainty, Strategic Finance*, 1993; **75**(4): 39.
12. Ghorbal-Blal I. The role of middle management in the execution of expansion strategies: The case of developers' selection of hotel projects, *Int J Hospital Manage* 2011; **30**(2): 272-82.
13. Nelson CA. A scoring model for flexible manufacturing systems project selection, *European J Operat Res* 1986; **24**: 346-59.

14. Anagnostopoulos KP, Petalas C. A fuzzy multicriteria benefit–cost approach for irrigation projects evaluation, *Agricult Water Manage* 2011; **98**(9): 1409-16.
15. Hassanzadeh F, Modarres M, Nemati HR, Amoako-Gyampah K. A robust R&D project portfolio optimization model for pharmaceutical contract research organizations, *Int J Product Econom* 2014; **158**: 18-27.
16. Liu SS, Wang CJ. Optimizing project selection and scheduling problems with time-dependent resource constraints, *Automat Construct* 2011; **20**(8): 1110-9.
17. Kyparisis GJ, Gupta SK, Ip CM. Project selection with discounted returns and multiple constraints, *European J Operat Res* 1996; **94**(1): 87-96.
18. Khalili-Damghani K, Sadi-Nezhad S, Tavana M. Solving multi-period project selection problems with fuzzy goal programming based on TOPSIS and a fuzzy preference relation, *Inform Sci* 2013; **252**: 42-61.
19. Heidenberger K. Dynamic project selection and funding under risk: A decision tree based MILP approach, *European J Operat Res* 1996; **95**(2): 284-98.
20. Grossman GM, Shapiro C. Dynamic R&D competition, *Econom J* 1987; **97**: 372-87.
21. Stahl MJ, Harrell AM. Identifying operative goals by modeling project selection decisions in research and development, *IEEE Transact Eng Manage* 1983; **30**(4): 223-8.
22. Schmidt RL, Freeland JR. Recent progress in modeling R&D project-selection processes, *IEEE Transact Eng Manage* 1992; **39**(2): 189-201.
23. Shakhsi-Niaei M, Torabi SA, Iranmanesh SH. A comprehensive framework for project selection problem under uncertainty and real-world constraints, *Comput Indust Eng* 2011; **61**(11): 226-37.
24. Martinsuo M, Korhonen T, Laine T. Identifying, framing and managing uncertainties in project portfolios, *Int J Project Manage* 2014; **32**(5): 732-46.
25. Luehrman TA. Investment opportunities as real options: Getting started on the numbers, *Harvard Business Rev* 1998; **76**: 51-61.
26. Li YF, Xie M, Goh TN. A study of project selection and feature weighting for analogy based software cost estimation, *J Syst Softw* 2009; **82**(2): 241-52.
27. Hall DL, Nauda A. An interactive approach for selection IR&D projects, *IEEE Transact Eng Manage* 1990; **37**(2): 126-33.
28. Sinha S, Thomson AI, Kumar B. A complexity index for the design process, *Proceedings of 13th International Conference on Engineering Design*, Glasgow, Scotland, 2001, pp. 157-63.
29. Baccarini D. The concept of project complexity-a review, *Int J Project Manage* 1996; **14**(4): 201-4.
30. Edmonds BM. *Syntactic Measures of Complexity*, Manchester, UK, University of Manchester, 1999.
31. Bocquet JC, Patay E, Schindler A, Dudezert A. How to build a design product and its end-product system? An original approach called SCOS, *Proceedings of International Conference on Engineering Design*, ICED'07, Paris, France, 2007, pp. 1-10.
32. Latva-Koivisto A. *Finding a Complexity Measure for Business Process Models*, Research report Helsinki University of Technology, Systems Analysis Laboratory, 2001.
33. Nassar KM, Hegab MY. Developing a complexity measure for schedules, *J Construct Eng Manage* 2006; **132**(6): 554-61.

34. Vidal L, Marle F, Bocquet JC. Measuring project complexity using the analytic hierarchy process, *Int J Project Manage* 2011; **29**(11): 718-27.
35. Kaimann RA. Coefficient of network complexity, *Manage Sci* 1974; **21**(2): 172-7.
36. Temperley HMV. *Graph Theory and Applications*, Ellis Horwood Ltd, England, 1981.
37. Haas KB. *Managing Complex Projects: A New Model*, *Management Concepts*, Vienna, VA, 2009.
38. Shannon CE, Weaver W. *The Mathematical Theory of Communication*, University of Illinois Press, USA, 1949.
39. Sackman H. *Delphi Assessment: Expert Opinion, Forecasting, and Group Process*, Rand Corp., Santa Monica, CA, 1974.
40. Okoli C, Pawlowski SD. The Delphi method as a research tool: an example, design considerations and application, *Inform Manage* 2004; **42**: 15-29.
41. Skulmoski GJ, Hartman FT, Krahn J. The Delphi method for graduate research, *J Inform Technol Educat: Res* 2007; **6**(1): 1–21.
42. Juran JM. *A History of Managing for Quality*, Irwin Professional Publishing, USA, 1995.
43. Chankong V, Haimes YY. *Multiobjective Decision Making: Theory and Methodology*, Courier Dover Publications, 2008.
44. Mavrotas G. Effective implementation of the ε-constraint method in multi-objective mathematical programming problems, *Appl Mathemat Comput* 2009; **213**(2): 455-65.