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A NEW APPROACH FOR SUBCONTRACTOR SELECTION IN THE CONSTRUCTION INDUSTRY BASED ON PORTFOLIO THEORY

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Abstract. Various challenges such as new technologies, growing complexity and competitive environment, require the main contractor to assign some of the project's tasks to other parties, the so-called subcontractors. Although subcontracting is a usual phenomenon in the construction industry, insufficient attention to the subcontractor selection strategy may pose some major threats to a project. Having in mind the significance of such risks, the optimization of subcontractor selection is essential for the success of the project. The importance of risk management in selecting subcontractors and the direct relation between risks and returns in most projects are two main motives for using the concept of portfolio in this paper. The main objective of this paper is to propose a model to allocate the best portion of project's task to some subcontractors in order to reach the optimized portfolio of subcontractors and main contractor. This is a new approach in the subcontractor management; therefore, after presenting the model, an illustrative example will be presented for better understanding.

Keywords: subcontractor, portfolio, genetic algorithm, fuzzy theory.

Introduction

Various specialties required for carrying out the construction projects (Yik *et al.* 2006), escaping from uncertainty and financial burden (Wadhwa, Ravinran 2007) and mitigation of dispensable costs (Mbachu 2008) are some of the most important reasons that cause main contractors (MCs) to carry out the project's tasks with the aid of other parties. MCs have perceived that the concentration on their core competencies is the key success factor in the present challenging environment. They need to avoid focusing on unimportant issues, especially on problems related to the project execution, in order to be freer to apply some strategies such as subcontracting, downsizing, outsourcing, etc. (Pryke 2009). Subcontracting is a popular concept in the construction industry (El-Mashaleh 2011). MCs tend to subcontract their unimportant or unfamiliar tasks to SCs for some reasons such as better management of cost, time and quality, doing specialty work, etc. (Ng, Tang 2008). Generally, SCs can be defined as a party collaborating with MCs based on their dexterities and proficiencies in the execution of construction projects. Regarding the SC selection problems, there are three issues, which are not properly considered in previous investigations. The first one is the networking function of construction projects. Usually, when MCs win a project, they separate it into some distinctive sections (Wang *et al.* 2001) and subcontract most of these sections to the SCs (Kumaraswamy, Matthews 2000). A fragmented structure is the conclusion of the subcontracting concept (Tserng, Lin 2002). Moreover, the result of fragmented structure of projects is that leads to act as a network so predecessors and successors tasks are the result of this concept. These relationships influence the SCs selection phase and consequently, bring forth some issues, which have not been properly considered in previous investigations.

The second issue is considering the risk. The construction industry is one of the most risky industries in the world (Abbasianjahromi, Rajaie 2012). Owing to the high effect of SCs on the success of projects, the optimization of SCs selection with respect to the risk is important. In most situations, risks and returns have a direct relation with each other. Usually, managing risky projects can bring noticeable returns to stakeholders. It is important to propose a model, which is capable of choosing SCs based on the proper optimization of the risk and return ratio. In this way, it is necessary to consider a project as a whole package, in which the selection should not be done separately. Cost benefit ratio is another aspect of SCs selection problem. MCs have limited resources; therefore, they are eager enough to get an optimized combination among their resources, subcontracted tasks and benefit in each construction project. When MCs subcontract a work, they share its benefit or loss with SCs.

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If an MC, which has the capability of carrying out some works, subcontracts them to SCs, it will decrease its benefit or loss considerably. As a result, trading off in subcontracting projects' tasks to SCs is an important issue.

In order to overcome these issues, developing a model in SCs selection, which considers this optimization problem, is essential. Unfortunately, practical attempts applied for SC selection in the real world are based on traditional approaches, which have serious deficiencies such as the overly limited time for selection, high levels of uncertainty, difficulties in judging quality (Tserng, Lin 2002), inattention to the dependencies, and etc.

When MCs divide a project to some sub-projects, the allocation of sub-projects to some prequalified SCs should be done based on some specific considerations such as their dependencies, trade-off between risk and return and optimization issues. In this situation, the combination of SCs can be considered as a portfolio. SCs portfolio is a group of SCs that work together and influence each other in the duration of a project. Evaluation, prioritization and selection of the best SCs, are the main concerns of SC portfolio management. According to the portfolio management principles, the allocation of sub -projects to SCs should be done based on the balance between risk and reward and should be aligned with the organization strategy (Cooper, Edgett 2003). Despite the issue, which is SC's selection is properly matched with the concept of portfolio selection, some challenges such as complexity of projects and dependencies among tasks lead to the difficulty of portfolio selection.

This paper tends to propose a framework for SC portfolio selection in the construction projects. The main concerns of this paper are modeling and formulating task dependencies, SC's dependencies and achieving a balance between risk and return in SC's selection in a construction project.

1. Literature review

This paper covers various concepts related to SCs in the construction industry. As a result, previous works in two main categories including SC selection and portfolio management in SCs issues are surveyed separately in this section.

1.1. SC selection

The right selection of SCs increases the probability of MCs' success in the construction projects (Yin *et al.* 2009). According to the importance of SC selection, previous investigators have presented different models. In Mbachu's (2008) work, the effective criteria in the capability evaluation of SCs for inviting them in the bidding process were investigated. He developed his research in South Africa. SCs were ranked by decision makers' opinions based on the identified criteria. Finally, three parameters including the weight of each decision maker, criteria weights and SCs' scores were considered in the selection of the best candidate. Wang *et al.* (2001) applied fuzzy logic and genetic algorithm for developing a fuzzy hybrid model in the selection of SCs. They divided projects into some sub-projects using fuzzy logic and assigned the best SC to each sub-project. Their main concern in the selection process was reaching the optimized cash flow during the project lifecycle. Inattention to the network nature of project's tasks and their dependencies are the most important deficiencies of their models. Ng and Luu (2008) aggregated the historical records of successful and unsuccessful SCs and presented a model based on case-based reasoning. Hartmann and Caerteling (2010) searched some criteria, which MCs have given more attention to. Their results showed that price was the most important criterion for MCs. Elazouni and Fikry (2000) opined about a DSS for allocating some tasks to SCs based on the optimization of cost and time. The problem of their model was inattention to the risk and quality in their framework. Arslan *et al.* (2008) proposed a web-based model for the selection of SCs. They developed 25 criteria for SCs' evaluation, but their model's shortage was setting the same weight for all the criteria. Yin *et al.* (2009) put forth a two-stage model. In the first step, capable SCs were selected. In the next step, prequalified SCs were evaluated based on the criteria, which are essential for carrying out sub-projects properly. They used DEA tools for selection of the best SC.

As described, most of the previous works considered the selection of SCs individually while the network nature of project's tasks causes models not to match the real situations. Moreover, literature surveys showed that most of the past studies developed a step by step structure; therefore, it should be an important consideration in developing the model.

1.2. Portfolio management in SCs issues

Furlan *et al.* (2009) surveyed the SCs' relation to MCs and its effect on their core competency. They found that changes in the SCs' relation portfolio lead to an alteration of their core competencies. Tserng and Lin (2002) were the only ones who investigated the use of portfolio theory in the SC selection. Their model divided projects into some sub-projects. They constituted all of the possible portfolios of the prequalified SCs and identified sub-projects. They selected the best combination of SCs according to the identified risk and return. Their web-based model was named ASAP. Their model had three problems. The first one was inattention to the dependencies among SCs. The second one was the approach, which they chose for risk calculation. They defined risk as a difference between cost and income and the last problem, as they stated in their paper, was the calculation of portfolios. They constituted all possible portfolios and finally picked up the best one. When the number of SCs increases, the number of combinations will grow rapidly and this approach would not be able to work properly.

Other than Tserng and Lin's work, there is no investigation in this area. In recent years, several investigations have been developed in the arrangement of relations between supplier and customer (Furlan *et al.* 2009; Wagner, Johnson 2004). Although there are some differences between SCs and suppliers, but they are mostly similar, especially with respect to their role in the supply chain. The concept of suppliers' participation in the project is dynamic. It means that the MC can alter and improve the performance of suppliers during dynamic process whereas the process is linear for SCs. They start their works from a certain point and terminate it in the end. The alteration and modification in SCs is not easy. In addition, in many circumstances, MCs can get some useful feedbacks from the performance of suppliers in each dynamic process but the performance of SCs can only be evaluated in the end of their works. Although there are some differences between suppliers and SCs, reviewing researches developed in the supplier portfolio helps the authors to develop their concept in the same way with respect to their differences and to customize their model based on the nature of construction projects. Kraljic (1983) presented a theory of purchasing from suppliers based on portfolio theory. His main idea was decreasing the vulnerability of customers in supplying their materials and increasing the purchasing power. He constituted four purchasing strategy portfolios and optimized the risk and returns. Tang and Rai (2011) concluded that if the portfolio is concentrated and the duration of relations is long, the dependency between suppliers and customers will increase. Langenberg *et al.* (2011) proposed a model for optimizing the allocation of the product portfolio to the portfolio of the supply chain. Their results showed that decision makers would be able considerably to reduce their costs by optimizing their supply chain and product portfolio. With respect to the results of the application of the portfolio concept in the supplier's area, it is necessary to develop more researches for adapting the concept of portfolio in the SCs area.

2. Model development

Generally, the concept of the paper's model is made up of two main categories: First, the development of the concept of portfolio for SC selection and second, solving a portfolio problem with the appropriate tools. The most important issue in developing the concept of portfolio to SC selection is assessing the combination of SCs instead of conducting SC selection individually. There are several combinations of SCs in each situation and the selected portfolio should be optimized based on the company's objectives. On the other hand, the diversity of the combinations of SCs in a project leads to the necessity of using an optimization tool. The details of the presented framework will be described as follows.

2.1. Developing the concept of portfolio for SC selection

Conducting the SC portfolio selection needs some considerations such as the combination of portfolio and various dependencies among SCs. Before describing this step, it is necessary to consider some rules as follows:

Rule 1: The project will be subdivided into some sections. This division can be done based on the project scheduling plan or according to the decision makers' opinions. For each sub-project, the best SC portfolio will be selected. The key point is that the order of tasks existing in each sub-project or the order of sub-project existing in the project is not changeable. In other words, this study aims at selecting the best SCs for some tasks in a fixed schedule. The decision makers cannot change the planning in order to obtain a better duration than the previous one.

Rule 2: All SCs who are candidate have passed the prequalification phase and have qualified for carrying out their duties.

Another concern of the authors is preparing prerequisites for organizing the probable portfolios. One of these issues is defining the dependency among SCs. The difference between portfolio theory and other approaches in the selection process is taking into account the dependencies among assets existing in the portfolio. The authors hypothesize some rules for the simplicity of solving this issue.

Rule 3: SCs' dependency can be categorized in two perspectives including SCs characteristics and project scheduling. In this paper, characteristic dependency and scheduling dependency named CD and SD respectively. The CD is considered when two or more SCs carry out one special task in the project. For example, if the excavation operations of a building are subcontracted to two or more SCs, the dependency among them can be considered as CD. In the same way, SD derives from the nature of project scheduling. For instance, SCs who perform the excavation of a building has a direct impact on the performance of the SCs who perform the formwork of foundation.

Rule 4: SCs in different sub-projects do not have any dependency on each other.

Rule 5: In the model implementation, the evaluation of MC is such as other SCs.

2.2. SC portfolio selection model

The main concern of portfolio theory is achieving a proportion of assets for maximizing the expected return and minimizing the risk. In this area, SC portfolio selection would be done for maximizing the expected return and minimizing the risk of the company. Whereas in most contractor companies, the nature of cost is more tangible than return, this paper changes its goal from maximizing the expected return to minimizing the expected total cost (ETC). Before presenting the equations, which formulate the concept of the paper, the most frequently used variables and notations are identified as follows:

n – number of SCs;

CD_{ij} – CD between i^{th} and j^{th} SCs. It's clear that when i^{th} and j^{th} SCs works in the same task $CD_{ij} = CD_{ji}$;

SD – the dependency among tasks;
PV – the total project value;
PD – the total project duration;
ns – number of sub-projects;
n' – number of SCs existed in k^{th} sub-project;
SPC_k – sub-project cost coefficient (between 0 and 1), $k = 1, 2, \ldots, ns$;
SPD_k – sub-project duration coefficient (between 0 and 1), $k = 1, 2, \ldots, ns$;
SCC_i – SC cost coefficient. It is estimated according to the contract price, which is suggested by MC. The proposed price by MC is equal to 1 and suggestions of other SCs are determined in proportion of MC's price;
SCD_i – SC duration coefficient. It is estimated according to the contract duration and project's planning. The proposed duration by MC in the project's planning is equal to 1 and other SCs' suggestions are determined in proportion of project's planning suggestions;
r_i – risk of i^{th} SC, $i = 1, 2, \ldots, n$;
w_{ik} – the percentage of job given to the i^{th} SCs in the k^{th} subproject;
CCS_{ik} – the cost of contract for i^{th} SC in the k^{th} subproject.

The objectives of this model are minimizing the cost and the risk of the selection of SCs. These two objectives are described in detail in what follows.

2.2.1. Expected total cost (ETC)

Regarding the nature of the construction industry and according to the experience of experts who have participated in this investigation, the ETC of SC selection is constituted of two major items including payment and management cost. These are described as follows:

- SC payment (SCP): this item speaks about the money, which MC directly pays to SCs according to their contracts. Suppose that the value of k^{th} subcontracted task is represented by $PV \times SPC_k \times w_{ik}$, the CCS_{ik} represents the coefficient of i^{th} SC for carrying out the mentioned task. The contract price of each SC or SCP is formulated as Eqn (1):

$$\mathrm{SCP}_k = \sum_{k=1}^{ns} \mathrm{PV} \times \mathrm{SPC}_k \times w_{ik} \times \mathrm{SCC}_{ik}. \quad (1)$$

- Management cost (MC): indeed, the more the SCs, the more the money necessary to coordinate them. Although the real value of this item needs to develop a separated research, the authors develop this item by a linear formula as follows:

$$\mathrm{MC} = ax + b, \quad (2)$$

where b is the constant value and a is a coefficient, which enhances the MC by increasing the number of SCs. The authors believe that obtaining this formula needs to develop another research but the linear equation is the simplest approach for formulating the concept of MC. The parameters of Eqn (2) are determined based on the expert judgment in each company.

2.2.2. Risk

Regarding the uncertainty existing in the decision making process, especially in SC selection, risk analysis is one of the important considerations. The risk evaluation of SCs can be carried out with the use of different tools. Previous investigators have had various considerations in this area. Owing to the highlighted role of experts' ideas in the decision making process in the construction industry, the authors applied fuzzy simple additive (FSAW) for estimating the risk of each SC. The SAW method is probably the best-known and most widely used MCDM method (Ravanshadnia *et al.* 2010). SAW can be transferred into fuzzy SAW by inserting the expert's judgments and working with linguistic terms. In this approach, each SC can obtain a score based on Eqn (3):

$$\tilde{R} = \sum_{n'=1}^{N'} w'_{n'} r_{n'i}, \quad (3)$$

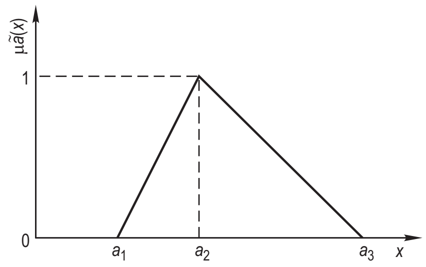
where $w'_{n'}$ is the weight of the n'^{th} risk and $r_{n'i}$ is the rate of the i^{th} SC with respect to the n'^{th} risk criterion. According to the recent expression, decision makers should evaluate SCs based on some criteria, which represent the risk of SC selection. These criteria can be very changeable regarding the nature of the project, environmental conditions, the company's considerations, qualified SCs, and etc. Therefore, the authors suggest that decision makers should develop their concerns in each project separately. Also, the members of the team, which develop the risks for evaluation of SCs should be selected among persons who have a strategic role in a project. As mentioned, parameters identified in Eqn (3) have the fuzzy nature. The linguistic terms presented in Table 1 are transferred to the fuzzy numbers and after different fuzzy calculations; the final fuzzy number of each SC will be generated. This fuzzy number will be diffuzzified to the crisp number for being applied in other steps with the use of Eqn (4) (for more information refer to Ravanshadnia *et al.* 2010):

$$R = \frac{\sum_{x_{\min}}^{x_{\max}} x\tilde{R}(x)}{\sum_{x_{\min}}^{x_{\max}} \tilde{R}(x)}. \quad (4)$$

After the risk of each SC was calculated, the calculation of CD is considered. Whenever a task is subcontracted to more than one SC, the calculation of the risk of each task is done with respect to the CD considerations and when the calculation of the risk of total project is considered, SD concept will be applied.

The CD value can be determined based on some criteria, which are applied for SC evaluation. For example, the proposed price and time, experience, available resources and SC risk value are some of them. The total value of characteristic dependency can be obtained as Eqn (5):

Table 1. Linguistic terms and their fuzzy members

Linguistic terms	Triangular fuzzy number	Triangular fuzzy number
Very good (VG)	(7.5 , 10 , 10)	
Good (G)	(5 , 7.5 , 10)	
Medium (M)	(2.5 , 5 , 7.5)	
Poor (P)	(0 , 2.5 , 5)	
Very poor (PL)	(0 , 0 , 2.5)	

$$\mathrm{CD}_{ij} = \frac{\sum_{m=1}^{M}\left(1-\frac{\left|r_{im}-r_{jm}\right|}{\max\limits_{m}\left(r_m\right)}\right)}{M}, \qquad (5)$$

where r_{1m} is the evaluated rate of 1^{th} SC with respect to the m^{th} criterion. After determining the CD among every two SCs, the total risk of each task can be calculated as Eqn (6):

$$R_{p_k} = \sum_{i=1}^{n} w_{ik}^2 r_i^2 + \sum_{i=1}\sum_{j \neq i} w_{ik} w_{jk} r_i r_j \mathrm{CD}_{ij}, \qquad (6)$$

where R_{p_k} represents the total risk of the k^{th} sub-project. i and j represent the index of each pair of SCs exited in the k^{th} sub-project. It should be noticed that $\mathrm{CD}_{ij} = \mathrm{CD}_{ji}$. According to the Eqn (5), if two SCs have positive or direct impact (positive dependency) on each other, the probability of failure or success of project will be increased. It is obvious that this strategy leads to increase the risk of portfolio. The main concern of portfolio concept is balancing the SCs' portfolio with assets, which are not perfectly positively correlated. In accordance with rule (4) SCs in other sub-projects do not have any effect on each other; but, because of the existence of SD among sub-projects, The total risk of the project can be calculated as follows:

$$R_p = \sum_{k=1}^{ns} R_{p_k} \times \mathrm{SPC}_k + \sum_{k=1}\sum_{k' \neq k} \mathrm{SPC}_k \mathrm{SPC}_{k'} R_{p_k} R_{p_{k'}} \mathrm{SD}_{kk'}. \qquad (7)$$

In the above formula $\mathrm{SD}_{kk'}$ is the dependency between k^{th} and k'^{th} sub-projects. Whenever there is a link between k^{th} and k'^{th} sub-project $\mathrm{SD}_{kk'} = 1$ otherwise $\mathrm{SD}_{kk'} = 0$. Unlike the CD, which CD_{ij} is equal to CD_{ji}, in the SD $\mathrm{SD}_{js} \neq \mathrm{SD}_{sj}$. For more understanding, refer to the previous example. For forming the foundation of a building, the excavation should be done first; therefore, the SD of formwork with excavation is equal to 1 while the SD of excavation and forming is 0.

The final goal of portfolio selection is reaching the best combination of SCs in a portfolio with the minimum risk and ETC. This goal has been formulated as Eqn (8):

$$\text{Minimize ETC and } R_p. \qquad (8)$$

There are some limitations in the optimization process. These limitations are presented as below:

- The completion time of the k^{th} sub-project is calculated with the following formula:

$$\sum_{i=1}^{n}\sum_{k=1}^{ns} \mathrm{SCD}_{ik} \times w_{ik} \times \mathrm{SPC}_k \times \mathrm{PV} \leq \sum_{k=1}^{ns} \mathrm{PD} \times \mathrm{SPD}_k. \qquad (9)$$

- The weight of SCs in each portfolio should not exceed from 1:

$$\sum_{i=1}^{n} w_{ik} = 1, \quad k = 1, 2, ..., ns. \qquad (10)$$

- Practical considerations lead to decision makers restrict the boundary of the subcontracted volume of tasks to SCs. A low volume of subcontracted tasks may bring a considerable overhead cost and a high volume of subcontracted tasks may jeopardize the goal of the projects. This limitation is formulated as follows:

$$A \leq w_{ik} \leq B, \quad k = 1, 2, ..., ns, \quad i = 1, 2, ..., n. \qquad (11)$$

A and B are constant values defined by decision makers in percentage format.

3. Solving the SC portfolio selection problem

Optimization approaches can be categorized into two main sections including conventional algorithms, which are capable of finding the precise answer, and new evolutionary algorithms, which find the nearest answer to the best solution. Solving most optimization models is too difficult with the use of conventional methods (Goldberg 1983). By simulating the natural processes, the evolutionary methods aim at solving optimization problems. There are various techniques for applying evolutionary methods for solving optimization problems. GA algorithm is one of the most successful tools (Goldberg 1983), which has been applied in many areas such as constrained or unconstrained optimization, scheduling and sequencing, transportation, reliability optimization, artificial intelligence (AI), and many others.

GA is a stochastic searching technique on the basis of mechanism of genetics and natural evolution (Goldberg 1983). In GA, potential solutions to the problem are encoded into the population of chromosomes. GA starts with choosing a group of random possible answers (called initial population). Then members are sorted in each generation by their fitness value, which can be calculated using the fitness function (ETC in this case). Just like natural evolution, the fitter a member is, the higher its chance of reproduction. As a result, parents with a higher fitness value are more probable to breed into offsprings and produce next generation. Offspring production uses a crossover and a mutation operator. As the number of generation grows, the generation converges to an optimization that satisfies the termination conditions.

This paper used Matlab's genetic algorithm function, which has provided engineers with a complete, simple and user-friendly atmosphere.

Selection, crossover and mutation function added with population size are important components of GA. In most cases, they use roulette wheel selection, one-point crossover and one-point mutation, which is poorly suitable for constrained optimization, also according to Lam *et al.* (2008), which compares three GA modules, the authors chose stochastic selection, two-point crossover and adaptive feasible mutations.

Population size is the number of members in a generation. Increasing the population size enables GA to search a broader space and reduce the diversity of answers. Default value was 100 but since it did not provide an accurate answer, the authors increased it to 10,000.

According to the obtained results of GA in several runs, the authors terminated the algorithm if the change in the average fitness value has been less than 10^{-6} for 50 consecutive generations. The authors found that with decreasing the value of 10^{-6} or increasing the number of generation, the final answers were not improved considerably.

This paper applied the constraint conditions to the fitness function. With this approach, the authors added a noticeable penalty, Penalty Cost (PC), to the fitness function if constraints have not been satisfied. It should be large enough so that those members that do not satisfy the constraint, would not be able to compete with those who do. As a result, GA will surely converge to an acceptable answer. On the other hand, it should not be too large or GA will converge to a relative optimum:

$$\text{CP} = \sum_{k=1}^{ns} \left(\sum_{i=1} w_{ik} - 1 \right) \times \text{PF}, \quad (12)$$

where PF (penalty factor) is 10^8.

4. Illustration

An example is designed in a hypothetical manner to illustrate the application of the proposed SC portfolio selection method, which involves the selection of the most appropriate SC among ten SCs (AL1to AL10). These SCs have passed the prequalification phase. The main problem is that MC wants to select the most appropriate SCs and assign them a specified volume for the project. For implementation of the authors' method and more concentration on each part of the project, the project should be sub-divided to sub-projects based on experts' opinions. It is proposed that the sub-project should be divided with the aim of project scheduling and the type of work. Regarding the project scheduling, each task can be defined in a network with the use of four relations including finish to start (FS), start to start (SS), start to finish (SF) and finish to finish (FF). The paper's example contains a project with five sub-projects with the network defined in Figure 1. Two parameters including the total cost and the completion time of each sub-project should be determined. Table 2 demonstrates this information.

Table 2. Project characteristic

Project total cost		23000000$
Project total duration		18 month
No sub-project	Cost coefficient	Duration coefficient
1	0.23	0.43
2	0.09	0.21
3	0.25	0.66
4	0.3	0.34
5	0.13	0.36

Pre-qualified SCs have been analyzed based on their characteristics, their risks, dependencies and estimated time and cost for performing the projects' tasks with a \$2000 value. The following tables demonstrate some required information for solving the present problem. Also, the dependency matrix of SCs is shown in Figure 2. Moreover, decision makers decide to restrict the subcontracted volume to 20% (bottom limit) and 100% (upper limit).

As previously stated, solving this problem is done with the use of Matlab software. The model's objectives and constraints were formulated and a graphical user

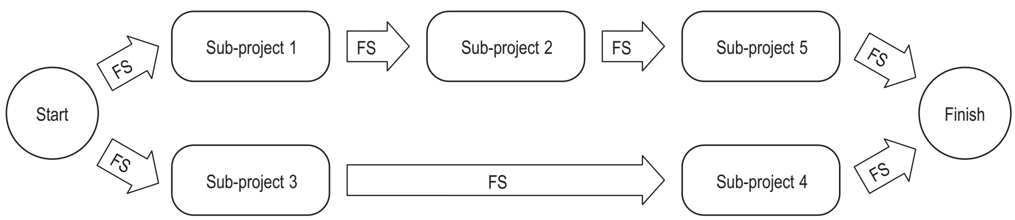


Fig. 1. The network of sub-projects

$$
CD=\begin{pmatrix}
1 & 0.793 & 0.88 & 0.875 & 0.848 & 0.742 & 0.801 & 0.89 & 0.777 & 0.837\\
0.794 & 1 & 0.714 & 0.676 & 0.939 & 0.535 & 0.916 & 0.71 & 0.57 & 0.631\\
0.88 & 0.714 & 1 & 0.949 & 0.769 & 0.821 & 0.721 & 0.929 & 0.856 & 0.911\\
0.875 & 0.676 & 0.949 & 1 & 0.73 & 0.86 & 0.683 & 0.966 & 0.895 & 0.956\\
0.848 & 0.939 & 0.769 & 0.73 & 1 & 0.59 & 0.922 & 0.764 & 0.652 & 0.686\\
0.742 & 0.535 & 0.821 & 0.86 & 0.59 & 1 & 0.543 & 0.826 & 0.952 & 0.904\\
0.801 & 0.916 & 0.721 & 0.683 & 0.922 & 0.543 & 1 & 0.717 & 0.578 & 0.639\\
0.89 & 0.71 & 0.929 & 0.966 & 0.764 & 0.826 & 0.717 & 1 & 0.861 & 0.922\\
0.777 & 0.57 & 0.856 & 0.895 & 0.625 & 0.952 & 0.578 & 0.861 & 1 & 0.939\\
0.837 & 0.631 & 0.911 & 0.956 & 0.686 & 0.904 & 0.639 & 0.922 & 0.939 & 1
\end{pmatrix}
$$

Fig. 2. CD matrix of SCs

Table 3. SCs characteristics

NO of SCs	SC's plus or minus coefficient	Needed time for	Estimated risk (0–1)
AL1	0.80	0.79	0.17
AL2	1.1	0.99	0.10
AL3	0.70	0.85	0.27
AL4	0.72	0.8	0.31
AL5(MC)	1	1	0.14
AL6	0.68	0.77	0.48
AL7	0.95	1	0.05
AL8	0.81	0.82	0.31
AL9	0.68	0.75	0.42
AL10	0.71	0.78	0.36

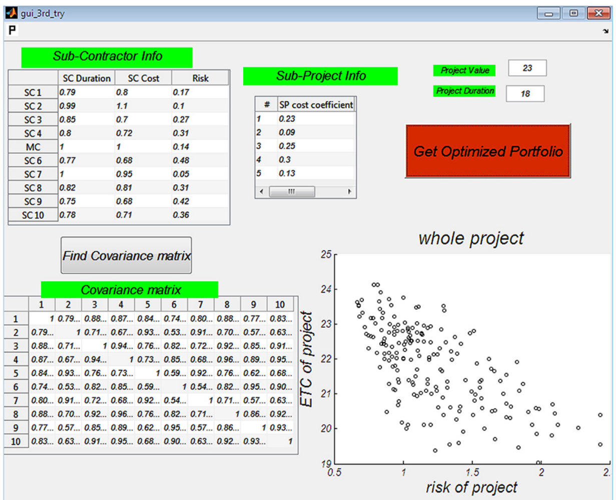


Fig. 3. SPST software

interference (GUI) tool called SPST (SC Portfolio Selection Tool) was developed for the users convenience. Figures 3 and 4 demonstrate the architecture of SPST software and some of its outputs.

After running the software with the given information, SPST presented several combinations of SCs. The best combinations, which have the lowest risk and ETC are known as efficient frontier. The combinations on the efficient frontier have the minimum ETC in the specific risk or vice versa. Moreover, point A and B have the lowest risk and ETC, respectively.

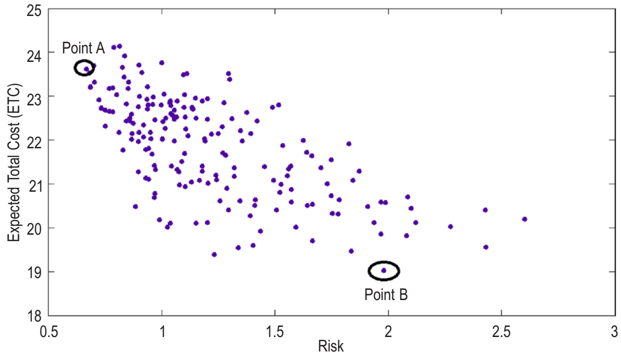


Fig. 4. The SPST outputs

Table 4. Information related to the combination with the lowest cost (Point B)

Point A: ETC = 19.03 Risk value = 1.98							
NO. SC	SC1	SC2	SC3	SC3	SC5	SC7	SC8
Percentage of job	1.00	0.74	1.00	0.65	0.35	0.25	1.00
Which sub project	4	1	5	3	3	1	2

Table 5. Information related to the combination with the lowest risk (Point A)

Point B: ETC = 23.62 Risk value = 0.67					
NO. SC	SC2		SC7		SC5
Percentage of job	100	100	100	100	100
Which sub project	5	3	4	1	2

5. Discussion

As explained in the introduction section, the main objective of this paper is proposing a model for selecting the best portfolio of SCs for a construction project. According to the literature survey, previous investigations opined that the proposed price of SCs, is an important criterion for SC selection. The traditional methods of SC selection pick up SCs based on one or some criteria for a specific subcontracted task but they do not consider the interaction of various SCs and their impact on project. Regarding the authors' point of view, the selection of SCs should be done with respect to the effect of related SCs on each other and optimizing the subcontracted tasks based on the characteristics of candidates. SC portfolio selection proposed by this paper can satisfy these goals. This paper takes into account two main criteria for evaluation of SCs, including cost and risk. Obviously, the cost parameter is the proposed contract price of SCs and other types of criteria for evaluation of SCs will be covered by applying risk parameter. Finally, the proposed method, with the aid of the concept of modern portfolio theory, presents some combinations of subcontracting project's tasks to some pre-evaluated SCs. The most important concept of this paper is modeling the SCs' dependencies. CD, which models the dependency of SCs with respect to their characteristics, and SD, which shows the dependency of sub-projects resulting from project's scheduling, are two parameters covering this modeling. Applying the paper's model helps decision-makers to manage their decisions in subcontracting according to their needs. Regarding the output of model (e.g. Fig. 4), decision makers can choose the best combination of SCs and subcontract tasks according to either of these strategies:

- Picking up the best combination of SCs according to the constant risk value;
- Picking up the best combination of SCs according to the constant cost value.

Figure 5 shows an example of the application of model. For example, if a decision maker wants to limit its selection to the combination of SCs in the risk value 1.5, he/she should draw a parallel line to the ETC axis from point 1.5 on the risk axis. The best combination is the first point where the line meets. Tsreng and Lin (2002) applied a portfolio concept for managing SCs as well. They opined that SCs in the construction projects are the same as investment assets in the market but they do not consider the dependency among SCs.

With respect to the new concept of this paper, an investigation on the obtained results is necessary. The authors review and discuss the various aspects of the results including the number of SCs, time and the best combinations.

5.1. Number of SCs considerations

As shown in Figure 6, raising the number of SCs increases the risk of project but as shown in Figure 7 there is not a clear relation between SCs and the cost of project. There are various risk and cost values in each number of SCs because of the different weights of allocated tasks to SCs and their various combinations. The decision makers would be able to select the best one according to their strategies.

For more understanding the relations among number of SCs, risk and cost of portfolios, the obtained portfolios in the cost of 23 million dollars are considered in Table 5.

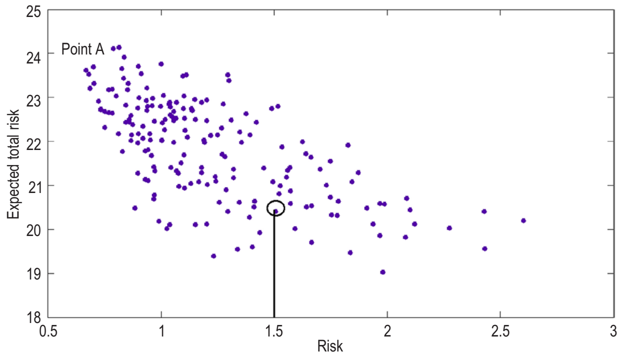


Fig. 5. An example of the application of model

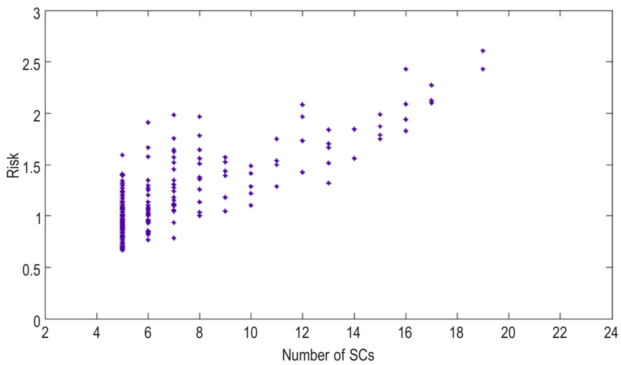


Fig. 6. The interaction of risk and number of SCs

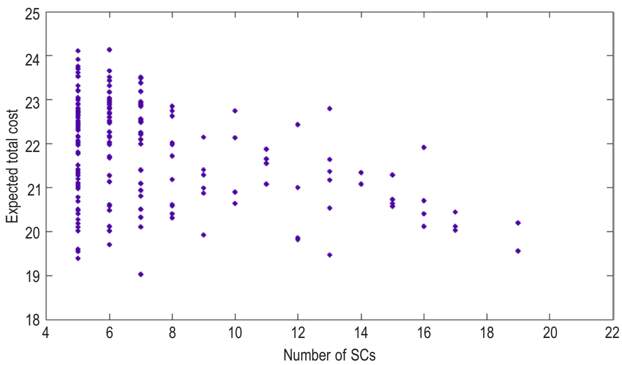


Fig. 7. The interaction of cost and number of SCs

Table 6. Portfolios' characteristics for ETC = 23

Choice No. 46 Risk = 1.01							
No. SC	SC2	SC3	SC5		SC7		
Which sub project	3	2	4	5	1		
Percentage of job	100	100	100	100	100		
Choice no. 134 Risk = 1.101							
No. SC	SC1	SC2		SC5	SC7	SC10	
Which sub project	5	4	3	3	1	2	
Percentage of job	100	100	80	20	100	100	
Choice no. 14 Risk = 1.15							
No. SC	SC1		SC2	SC3	SC5		SC7
Which sub project	1	2	4	2	5	3	1
Percentage of job	36	30	100	70	100	100	64

5.2. Time and risk consideration

The authors categorized the various combinations of results based on their durations. The authors defined some intervals less than, equal to or more than the time of the project. Figure 8 depicts this statement schematically.

Developing a figure such as Figure 8, helps decision makers to evaluate the potential of their selected portfolio to complete the task on time. Another figure (Fig. 9) can be developed for understanding the interaction of risk and cost with time.

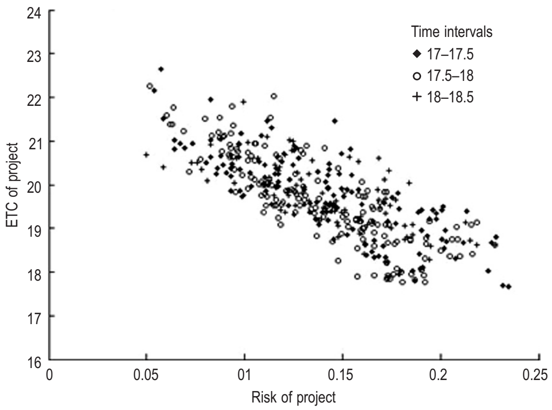


Fig. 8. Categorization of results based on their duration

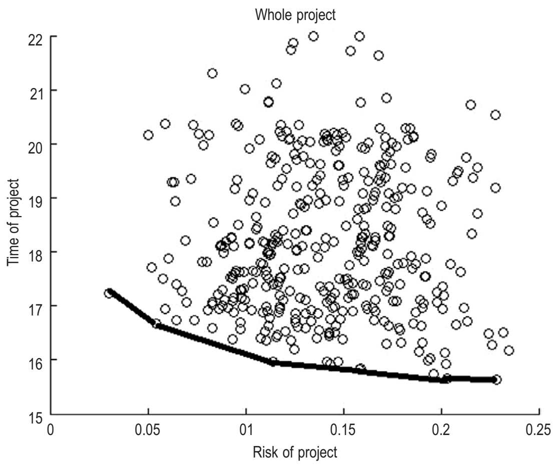


Fig. 9. The interaction of time and risk

In the above figure, all of the obtained results were investigated based on the time and the risk interaction. It is obvious that a reduction in the duration of the project with the use of portfolio theory can lead to an increase in the risk of project.

5.3. Best portfolios

In this section, the combinations of some portfolios on the efficient frontier are considered. Table 6 shows their characteristics.

As shown in Table (7), as the risk value decreases, the number of SCs is reduced. For example, in the lowest cost, there are six SCs, while in the lowest risk there are just three SCs. It is obvious that the impact of SC's dependencies increases the total risk.

Table 7. Characteristics of portfolio on the efficient frontier

Point 4: ETC = 19.03 Risk value = 1.98							
No. SC	SC1	SC2	SC3		SC5	SC7	SC8
Percentage of job	100	74	100	65	35	25	100
Which sub project	4	1	5	3	3	1	2
Point 149: ETC = 19.39 Risk value = 1.23							
No. SC	SC1	SC2	SC3	SC5	SC7		
Percentage of job	100	100	100	100	100		
Which sub project	3	1	5	2	4		
Point 21: ETC = 20.01 Risk value = 1.02							
No. SC	SC1		SC2	SC3	SC7		
Percentage of job	100	62	38	100	100	100	
Which sub project	3	2	2	5	4	1	
Point 132: ETC = 20.18 Risk value = 0.99							
No. SC	SC1	SC3	SC5	SC7			
Percentage of job	100	100	100	100	100		
Which sub project	3	5	2	4	1		
Point 126: ETC = 20.48 Risk value = 0.88							
No. SC	SC1		SC5	SC7			
Percentage of job	100	100	100	100	100		
Which sub project	3	5	2	1	4		
Point 164: ETC = 21.76 Risk value = 0.83							
No. SC	SC1		SC5	SC7			
Percentage of job	100	100	100	100	100		
Which sub project	2	5	3	1	4		
Point 158: ETC = 22.3 Risk value = 0.75							
No. SC	SC1		SC2	SC7			
Percentage of job	100	100	100	100	100		
Which sub project	2	5	3	1	4		
Point 86: ETC = 22.72 Risk value = 0.73							
No. SC	SC1	SC2	SC5	SC7			
Percentage of job	100	100	100	100	100		
Which sub project	5	3	2	1	4		
Point 43: ETC = 23.21 Risk value = 0.69							
No. SC	SC1	SC2		SC7			
Percentage of job	100	100	100	100	100		
Which sub project	2	3	5	1	4		
Point 65: ETC = 23.62 Risk value = 0.67							
No. SC	SC2		SC7		SC5		
Percentage of job	100	100	100	100	100		
Which sub project	5	3	4	1	2		

Conclusions

This paper applied a new concept in the management of SCs. Regarding the various advantages of portfolio theory, for instance, the optimization of benefit and risk in different selection problems such as stock market, project selection, supplier relationships and etc., the authors applied a portfolio concept in the selection and assigned the best portion of the projects to some prequalified SCs.

The main contribution of this paper is applying the modern portfolio theory, which is used in the stock market and interdependencies among SCs for calculating their risks. Most of the previous investigations, which are developed for SC selection have considered the characteristics of one SC, but this paper attempts to consider the interactions of SCs in each project with the use of portfolio theory. The most important benefit of this concept is that MCs can optimize their SC portfolio in the tendering phase, and then suggest their mark up with respect to the constituted portfolio of their SCs. Regarding the variable nature of construction projects, this portfolio can be updated when contractors need to select SCs for a specific job that had not been considered before. They can simply refer to their first SC portfolio and pick up SCs with the most similarities.

Regarding the characteristics of the proposed model, the application of fuzzy theory, MADM approaches and GA help this model to be comprehensive and applicable in different situations, such as when decision makers face lack of information for calculating their parameters or have uncertainty in their decisions. Moreover, developing a software increases the user-friendliness of a paper's framework. SPST can help decision makers in SC portfolio selection by easing calculation and saving time.

As the authors identify the various aspects of this concept, the subjects below can be considered as future works:

1. Interdependency of SCs is one of the areas, which can be further developed in researches. Further investigations can survey the impact of interdependency on the key criteria of this problem such as cost, time and risk.

2. Regarding the importance of management cost in the evaluation of total cost of SCs, it is proposed that a separated research can be conducted in the evaluation of these parameters.

3. Apart from GA, other optimization tools such as particle swarm optimization (PSO), ant colony optimization (ACO), bee algorithm (BA), etc. can be considered and their differences should be reviewed.

4. Other investigations can be developed for proposing an optimized network of sub-projects based on the SC portfolio selection.

5. This paper applied SC portfolio management in a project, but it can be developed to the SC portfolio of a company. In this case, some considerations such as interdependency of projects in the portfolio of a company and the cash flow of the company also become very important.

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