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# DIVIDE-AND-CONQUER: A SYSTEMATIC APPROACH FOR SUBCONTRACTOR SELECTION IN DEFENSE INDUSTRY PROJECTS

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Defense industry projects generally are of large size and may be broken down into subparts of different granularity levels, where each subpart may be assigned to a different subcontractor. On the other hand, the problem of subcontractor selection to each subpart is a complex decision-making problem that requires evaluating a number of criteria and the characteristics of each subpart. This study aims to model the problem of subcontractor selection in a defense industry project decomposed to multiple subprojects by combining the Analytic Hierarchy Process (AHP) and Integer Linear Programming (ILP). A project carried out at a defense industry company in Turkey has been used as a case study. An extensive set of criteria specific to the defense industry have been identified, and AHP has been applied to the relevant criteria and alternative subcontractors for each subpart. Finally, ILP has been used to include a set of constraints regarding the project specifications.

**Keywords:** Subcontractor Selection; Defense Industry; Project Decomposition; Analytic Hierarchy Process (AHP); Integer Linear Programming (ILP)

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## 1. INTRODUCTION

The defense industry is accepted as one of the most effective power factors of economic and political authority, and as a result, governments emphasize its development and expansion (Baran, 2018) (The Union of Chambers and Commodity Exchanges of Turkey - Council of Defense Industry Sector, 2017). Military spending worldwide increased by 3.6% compared to the previous year in 2019, the largest increase since 2010, becoming a total of $1,917 billion (Stockholm International Peace Research Institute, 2020). Due to political reasons and high-level competition between defense industry companies, it is difficult to export defense products to foreign countries (Ziylan, 2004). Moreover, defense industry companies need to employ efficient R&D approaches to acquire successful technological innovations, production, and operational activities due to the high level of uncertainty and the need for large investment in the industry (Lee and Park, 2019). Therefore, companies operating in this industry are required to have large-scale organizational structures in order to develop high technology defense systems that necessitate a high level of R&D investment. However, there are just a couple of companies of this size globally that may be defined as "main national contractors," whereas a wide range of small and medium-sized companies are operating as subcontractors of these large-scale companies in the sector (Ziylan, 2004). Main contractors can be defined as the companies that sign projects with customers, whereas subcontractors are the companies that main contractors assign some part of the signed project. Customers are generally referred to as end-user authorities or the governmental institutions that make tenders. The defense industry requires the specialization of companies in certain categories of businesses and working on a project basis rather than continuous production on assembly lines. Weapon systems, radars, and electro-optics are all different kinds of domains, where each product requires its own know-how to be built. Because of this differentiation in the sector, dividing the project into parts is a frequently used method by the companies. By subcontracting, the project's main contractor finds the chance to use some other company's specialized and detailed knowledge regarding a specific area to complete the overall project. With the use of this business approach, main contractors may adjust the labor that they need via subcontractors, while the subcontractors enhance their workloads. Moreover, it becomes an opportunity for small-sized companies to specialize in certain niche areas in the overall defense industry.

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A subcontractor may be considered as a supplier to the customer, as it supplies not only goods but also services. Therefore, the problem of subcontractor selection may be approached as a supplier selection problem. Companies progressively attach importance to better supplier selection methods to accomplish their low cost, continuous quality, and flexibility goals. Current business trends, including increased rates of technological change, shortened product life cycles, and foreign sourcing, have increased the need for improved communication and cooperation between the buyer and supplier companies, thus increasing the importance of supplier selection decisions (Nydick and Hill, 1992). Since the supplier selection process requires considering different organizational characteristics, such as production quality, purchasing details, product guarantee, and in-house production, this problem may be defined as a multiple objective decision-making problem with a number of tangible and intangible factors that have a hierarchical structure (Quigley, 1995). Supplier companies may be evaluated with respect to several criteria, such as product price, delivery (timeliness and cost), quality, and service features (labor force, skills, resources, etc.). However, these factors may involve some tradeoffs. For instance, one supplier may offer cheaper products with lower quality, while another supplier may offer higher quality products with some unsettled delay period. Such criteria are divided into two classes as qualitative and quantitative, and the importance of each criterion may differ from one product to another. A method is needed to embody the remarks of the decision-maker about the importance of each criterion and to connect qualitative and quantitative pieces (Bhutta & Huq, 2002). Multi-Criteria Decision Making (MCDM) methods are frequently used to evaluate alternatives according to qualitative and quantitative criteria, and Analytic Hierarchy Process (AHP), a well-known MCDM method, is commonly used in contractor or subcontractor selection and prequalification studies (Thummala and Rao, 2011; Tam and Tummala, 2001; Liberatore, 1987).

Generally, large projects and in specific defense industry projects may be assigned to one or more subcontractors wholly or partly. Defense industry projects in their majority are so large-sized that even if some parts of the overall project are assigned to subcontractors, this still may correspond to a significant size, which may require further decomposition. Another point to consider is that the subcontractors may not be qualified as required for every subpart of the project in consideration. To optimize the assignment process of subcontractors to project parts, each part may be evaluated within itself by assessing the proper subcontractors for the corresponding project part. For instance, rather than assigning a project part that requires the development of two different software in different fields of work to a single subcontractor, the project part may be further divided into two subparts with respect to two different software in question, and the proper subcontractors may be evaluated for the subparts separately. In this way, it is considered that the suitability of subcontractors would be measured more precisely with the decomposition of the project into parts.

In literature, briefly summarized in section 2, a variety of techniques have been used for subcontractor selection in different industries. Most of the subcontractor selection problems in previous studies were classified as MCDM problems, and the AHP could be classified as the most common solution method for these problems. Unlike the previous studies, we propose a novel way of MCDM for subcontractor selection by decomposing the project into subparts before subcontractor evaluation. In this way, rather than a single subcontractor for the complete project, a set of subcontractors for each project part is obtained. Problem constraints are considered in the next step with an optimization model in combination with the MCDM results and the final optimal set of subcontractors is found. Moreover, in this study, the subcontractor selection process in a defense industry company has been considered from a different viewpoint by considering the special characteristics and conditions of defense industry projects. With respect to these, four research questions have been formulated, and are addressed with the methodologies employed in this study:

| | |
|---|---|
| **Research Question 1 (RQ1):** | What should be the criteria set to evaluate subcontractors for defense industry projects? |
| **Research Question 2 (RQ2):** | How feasible is it to decompose the project into parts and apply MCDM for each subpart? |
| **Research Question 3 (RQ3):** | How meaningful is it to choose subcontractors for each decomposed project part by the application of MCDM? |
| **Research Question 4 (RQ4):** | How can we find an optimal set of subcontractors using weights for alternatives and taking a set of constraints into consideration? |

The nomenclature that is used in the following sections are briefly explained below:

| | |
|---|---|
| **Customer:** | The end-user or the organization that manages the business process on behalf of the end-user. |
| **Main Contractor:** | The project owner company is assigned by the customer. |
| **Subcontractor:** | The companies selected by the main contractor to complete some parts of the project. |

The rest of the paper is organized as follows: Section 2 provides a detailed literature review of related studies, whereas section 3 provides brief information regarding project decomposition, the chosen MCDM technique (AHP) and Integer Linear

Programming (ILP), and how these three approaches are combined to answer the aforementioned research questions. The application of the proposed methodology to the defense industry is given in section 4. The paper continues with a case study in section 5, and the solution model has been assessed regarding its effectiveness in section 6.

## 2. LITERATURE REVIEW

There are several studies in which AHP has been employed with different techniques such as PROMETHEE II (Can and Arıkan, 2014), TOPSIS (Lo, Chen and Liu, 2018), goal programming (Dağdeviren and Eren, 2001) or DEMATEL (Chang and Chen, 2011) for contractor/subcontractor selection problems. In Table 1, we present the major studies in which AHP has been used with other techniques for the problem of selecting suppliers or subcontractors for projects from different domains. This literature review has provided the current study with a possible list of criteria (Table 2) and how AHP can be used together with ILP.

Table 1. List of Major Studies of Literature Review

| **Study Name** | **Major Findings** |
|---|---|
| Ho *et al.* (2010) | A detailed review of 78 journal articles that address the supplier selection problem, focusing on the methods used to solve these problems. As the authors state, mathematical programming methods (linear programming, ILP, integer non-linear programming, goal programming, and multi-objective programming), AHP, Analytic Network Process (ANP), Fuzzy Set Theory, Case-based Reasoning (CBR), Simple Multi-attribute Rating Technique (SMART) and Genetic Algorithm (GA) were mainly used as individual approaches for supplier selection. Integration of AHP and Mathematical and Fuzzy Methods were also applied frequently for supplier selection decision-making problems. |
| Al-Subhi Al-Harbi (2001) | The study uses AHP in project management and constructs a contractor prequalification example. By performing the method, the author developed a prioritization for pre-defined criteria and a descending-order list of subcontractor candidates to select the subcontractors that best suit the project characteristics. Financial stability, experience, manpower resources, quality performance, equipment resources, and current workload were determined as the criteria set. The author compared four subcontractors in a descriptions table where each criterion has its own attributes. In the end, a priority order of subcontractors was found with their respective AHP weights. |
| Bhutta and Huq (2002) | The authors compare Total Cost of Ownership and AHP methods to address a supplier selection problem. They compared the two methods with respect to several criteria and presented a feature list about their procedures, decision-making situations, advantages, disadvantages, and applications. Both techniques are found useful in the supplier selection process. However, AHP is described as a more robust tool to evaluate and choose suppliers. |
| Öztürk *et al.* (2011) | The authors illustrated the evaluation of suppliers in a textile industry company and used AHP as the utilized MCDM method. The authors proposed a model which consists of five alternatives, seven main criteria, and 13 sub criteria. To evaluate the sub criteria and alternatives, a research team from various departments of the organizational structure such as production, purchasing, quality, marketing, IT, and R&D was formed. This team was used as a focus group, and they shared their opinions in focus group discussions till they reached a consensus. The group's decision was used in pairwise comparison matrices as single decision maker. The results defined the most important criterion as quality, followed by technical capacity, cost, experience/eagerness to job, options/promotions, and financial capacity, respectively. Regarding the comparison of alternatives by taking the criteria set into consideration, a ranking of alternatives was found to be used for the coming production period. |
| Acar *et al.* (2015) | The authors propose a methodology that integrates AHP, geographic information systems, and integer programming to determine the locations of the regional return centers for reverse logistics. In this study, population, airport locations, maritime facilities, railroad lines, and highway lines are used as the decision criteria, AHP is employed to determine the city groups and the criteria weights, whereas integer programming is used to optimize reverse logistics network based on the output values produced by the geographic information system. |

| **Study Name** | **Major Findings** |
|---|---|
| Partovi *et al.* (1990) | The authors focus on potential applications of AHP in production and operations management and use the expertise and judgment of managers to prioritize information for more reliable decisions by presenting the use of AHP in eight different decision-making processes, namely plant layout design decisions, product design decisions, preventive maintenance frequency decisions, choice of technology, facility location planning, supplier selection decision, choice of logistic carrier and time series forecasting adjustments. Eight different AHP hierarchies with goals, criteria, and alternatives were developed to demonstrate the wide range of multiple factor operational decisions for which AHP may be employed. For the process of supplier selection, four main criteria and eight sub criteria were used to evaluate three vendors. The main criteria were quality, delivery, pricing structure, and service. As the authors have stated, the suggested AHP models offer a more reliable procedure than ad hoc or other existing methods that need laboratory or field testing. |
| Liberatore (1987) | The study expresses that project selection decisions should be connected to the plans and strategic goals of the corporations. The research focused on allocating resources to a set of projects, and an AHP model has been built to reflect the corporate and R&D planning processes. The focus of the selection process was determined as the firm's future strategy, where three scenarios to achieve the focus of the hierarchy were identified at the secondary level, namely maintain existing businesses, expand existing businesses, and diversifying into new businesses. Product R&D, process R&D, and exploratory R&D were selected as actors to achieve scenarios at the third level, whereas criteria and sub criteria were placed at the fourth and fifth levels of each actor. Liberatore suggested alternative uses of AHP because of the infeasibility of pairwise comparisons in case there is a large number of projects to evaluate. A spreadsheet model that was linked with AHP was used where four rating levels, namely outstanding, above average, average, and below average, were determined to rate R&D projects. Alternatively, the 0-1 ILP approach was proposed by the author. The objective of the problem was determined as maximization of total priority over all funded projects subject to a monetary constraint and possibly other restrictions. |
| Chan (2003) | The study presents an interactive subcontractor selection model to expedite the subcontractor selection process for decision-makers. A novel method named Chain of Interaction was proposed to overcome human judgment in determining the importance of factors. The model focused on the earlier steps of AHP, such as identification of buyer-supplier relationships and formulation of decision criteria. The author defined five levels to categorize buyer-supplier relationships and assigned four parameters like a product, process, human resources, and technology to define the scope of relationships. A criteria set was identified, and each criterion was marked with a tick if it's relevant for the level of relationship. In the numerical example, four suppliers were evaluated with interactive selection models and AHP to find the optimal alternative. |
| Chan *et al.* (2007) | The authors proposed an AHP-based decision-making approach for the problem of supplier selection in the airline industry. Three assessment areas, namely performance assessment, continuous improvement and innovation, and company background/business structure, were defined to evaluate alternatives. For each assessment area, several criteria were defined, with several sub criteria in the lower level. The authors presented explanations and justifications for each criterion and sub criteria and applied AHP for the complete problem. In the end, sensitivity analysis was conducted to improve the validity of the results and understand the importance of various criteria regarding final decision. |
| Sarkar and Mohapatra (2006) | The authors have approached the supplier selection problem from a different angle by identifying the range of supply base as an important problem for developing a partnership with suppliers and presenting a systematic framework for reducing the supply base. They suggested the use of performance and capability as two vital measures for evaluation and selection problems of subcontractors. They used a fuzzy set approach to measure the imprecision of the factors and rank a potential list of suppliers. A capability-performance matrix was created to rank the suppliers based on expert opinions. The experts ranked the alternatives with a fuzzy scale against each factor. The location of each alternative in the performance and capability matrix represented the ranking of each supplier. |

| **Study Name** | **Major Findings** |
|---|---|
| Chen *et al.* (2020) | A three-stage decision-making model that consists of Quality Function Deployment (QFD), AHP, and Improved Grey Correlation Analysis (IGCA) for subcontractor selection in a construction enterprise is introduced. The authors offered a new way of selection method by considering the demands of the enterprise. Mainly, QFD was used as a tool for transforming company requirements, while AHP-IGCA was used to calculate the weights of evaluation indicators. The indicator's weighting was composed of two stages where the initial weight of the indicators based on subjective judgments was calculated by using AHP first. Then subjective judgment matrix was processed with IGCA to find the final weights of indicators. |
| Wang and Tsai (2018) | In this study, a fuzzy MCDM approach that consists of Fuzzy AHP (FAHP) and Data Envelopment Analysis (DEA) is proposed to evaluate suppliers for solar panels. As the authors stated, to eliminate the dependency of FAHP to input data such as the experience of experts, the DEA model was used to rank potential suppliers in the final stage of evaluation. Lead time and unit price were defined as inputs, while the DEA model specified qualitative benefits and cost savings as outputs. |
| Wang *et al.* (2019) | By stating the importance of purchasing raw materials in the plastics industry, the authors propose an MCDM model for supplier selection for raw materials. The study uses Supply Chain Operation Reference (SCOR) Model, Fuzzy Analytic Network Process (FANP), and VIKOR to evaluate and select suppliers. A set of main criteria and sub criteria were defined to assess potential suppliers based on SCOR metrics. Whereas the weights of all criteria were found with FANP, the alternative suppliers were ranked using VIKOR. |

## 3. RESEARCH METHODOLOGY

Subcontractor selection is a complex problem and may require to consider many criteria. Even though the related job is given to the subcontractor to be built, the whole responsibility belongs to the main contractor in the eye of the customer. Also, when it comes to the development of defense projects, even the least significant factor may be of vital importance. In this regard, companies should put proper emphasis on the subcontracting process. As the defense industry has certain expertise areas and knowledge domains, subcontracting by dividing the project into small parts to select the companies that fit best with the related job is an appropriate practice. This is a risk-minimizing method if it can be applied by considering all the relevant criteria objectively.

The methodology employed in this research to answer the question of assigning a large defense industry project to multiple subcontractors is a combination of project decomposition AHP and ILP. The proposed process begins with the project decomposition part and continues basically with determining the criteria set, AHP application, and ILP model. By using AHP, a ranking of subcontractor candidates for pre-divided parts of the defense projects can be determined. Each part of the project may be evaluated in itself regarding the relevant criteria with pairwise comparison matrices to reach an order of priority with the weights of the alternatives. The analysis continues with the use of ILP to integrate the results of the AHP with the constraints of the problem to find a final solution. A brief explanation of each step is given in the following sections, whereas the steps of the methodology are expressed with the following pseudocode and the flowchart given in Figure 1. Figure 1 also shows the major output that is produced at the end of the model (list of chosen subcontractors) but also any intermediate outputs during the execution of the model (project decomposition, criteria set, alternative subcontractors, optimization model, list of constraints, and AHP weights) and the stages of execution (project decomposition, criteria selection, AHP application, and ILP execution).

**Pseudocode** of proposed methodology

***Set*** the whole project to the top *(Level 0)*
***Divide*** the project into *n* parts *(Level 1)*
***for each*** part
    ***if*** required to divide the part to subparts
        ***divide*** the part into subparts and add subparts project decomposition
***Define*** the criteria set based on literature and expert opinions
***Apply*** a questionnaire regarding the importance of the criteria
    ***for each criterion*** in criteria set
        ***if*** the criterion is greater than or equal to cutoff value, keep it in the criteria set
        ***else*** exclude from the criteria set
***Choose*** which criteria should be considered for which project part
***Define*** the alternative subcontractors
***for each*** subpart in *Level m*
    ***Apply*** the AHP
    ***find*** the ranking and weights of alternatives for each subpart in *Level m*
***Define*** the constraints
***Build*** an optimization model with ILP **by defining the objective function as maximization of AHP weights**
***Execute*** the ILP model by using the constraints of the problem in the model
***List*** the subcontractors chosen

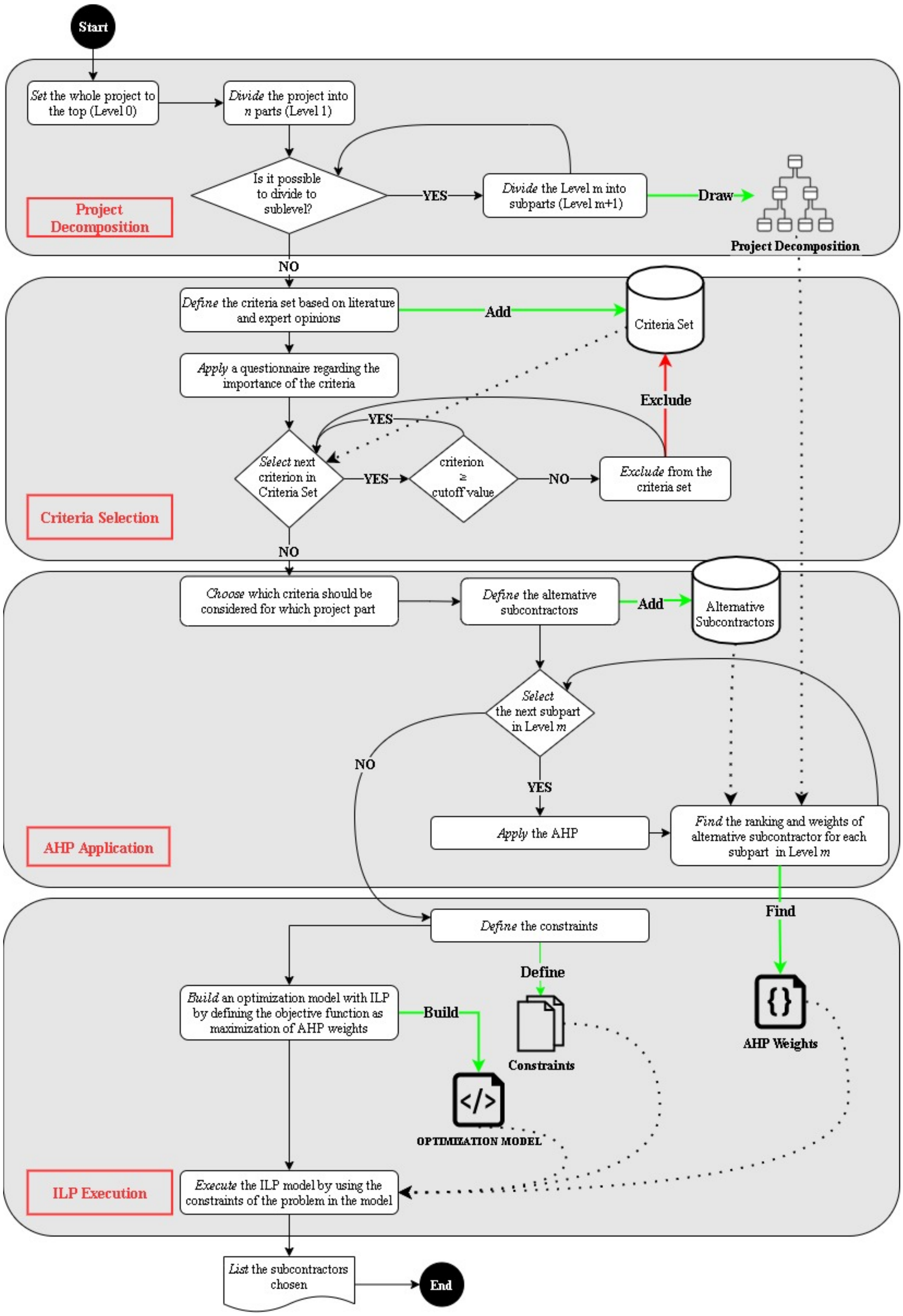


Figure 1. Flowchart of the proposed methodology

### 3.1 Project Decomposition

Defense industry projects, by their nature, are large-scale and complex projects. Patanakul *et al.* (2016) argue that to deal with the complexity of such large-scale projects, it is recommended to modularize the project to subprojects, in other words, to decompose the projects to better manageable subparts. Moreover, defense industry projects are usually large projects that consist of easily distinguishable smaller parts when they compound together and form a complete product. In this view, working with a sufficient number of subcontractors specializing in their areas of work provides an advantage to the main contractor.

When subcontracting a project or a part of the project, it is important to find subcontractors suitable to the characteristics of the work that will be assigned. If the work appeals to a wide range of businesses, assigning the whole work to a single subcontractor will be risky because of the potential lack of sufficient know-how in every aspect of the project. Hence, this study suggests decomposing and modularizing the project into smaller parts planned to be assigned to subcontractors. These smaller parts that remain under different levels of the main project are named subprojects. Pinto (2016) defines a subproject as smaller components of the overall project formed when a project is subdivided into more controllable components or pieces. The subprojects may be treated as single independent projects and may be assigned to different subcontractors. By using this method, the main contractor would utilize the expertise of specialized subcontractors and spread the risk of failure for each part of the project. Establishing subprojects was suggested as an alternative approach under route map fragments, and three options have been chosen as follows:

- Process-oriented denotes decomposition into subprojects based on subprocesses.
- System-oriented denotes decomposition into subprojects based on subsystems.
- Hybrid denotes decomposition into subprojects partially based on subprocesses and partially on subsystems.

In the current study, the notation for the decomposition of the project part consists of n number of levels from top to bottom, similar to the hybrid subproject definition by van Slooten and Hodes (1996). The top-level symbolizes the main project part, which is planned to be assigned to one or more subcontractors, while the bottom level denotes the smallest part of the project part that is reasonable to be assigned to a subcontractor. Project decomposition is visualized in Figure 2, where the subparts of the same parent nodes are shown as clusters. The number of clusters is equal to the number of parts shown in Level 1. Even though the clusters are shown equally in the figure, not all project parts have to be comprised of subparts.

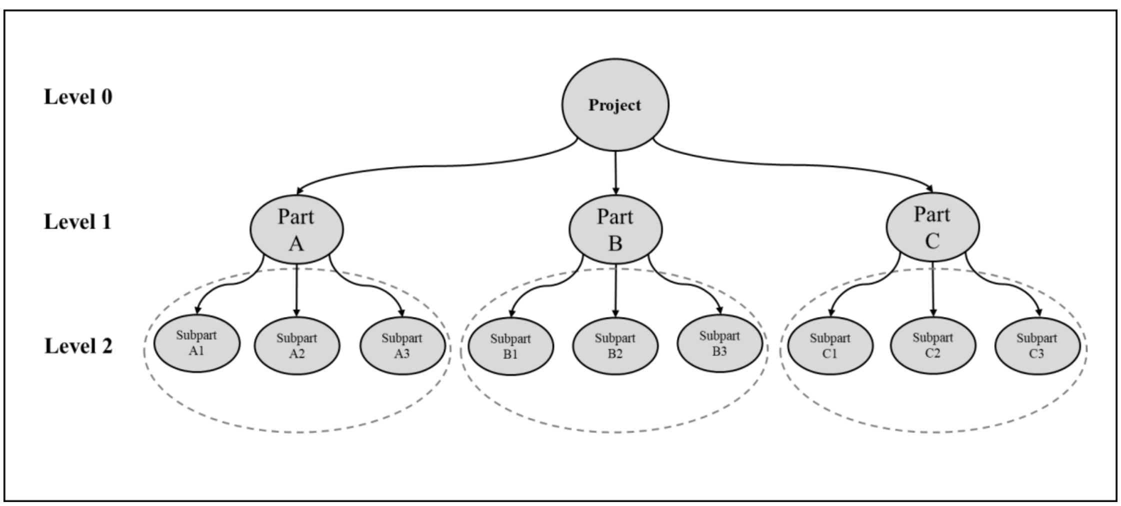


Figure 2. Project Decomposition

The discrimination between parts in the same level can be either different sub-units of products or different work types such as hardware, software, etc. The number of levels and number of subparts in each level may be determined depending on the decision makers' choices regarding their perspectives about the project parts. Although this study suggests decomposing the project into smaller parts, the maximum number of levels and minimum size of the subparts should be identified carefully. Using numerous subparts would make the project complicated to manage and may jeopardize the success of the project. Likewise, classifying very small parts of work as subprojects would also be ineffective for the project management. In this way, rather than creating an advantage for the project, project management would become a more difficult process. Following the decomposition step, the decision-making process will be applied to each subpart in the lowest level of the project part.

### 3.2 Analytic Hierarchy Process (AHP)

AHP, developed by Saaty (1980), is an MCDM method (Carlsson and Fulier, 1996) that prioritizes alternatives regarding evaluating several criteria. It presents a framework to deal with subjective and nonrational criteria to reach a solution that fits best with the organization's goals. Researchers have argued that AHP provides a visual appearance with at least two layers of the hierarchical structure. Even though it is a decision-making method for complex problems, simplicity is a favored feature of AHP (Liberatore, 1987; Schoemaker and Waid, 1982). Schniederjans and Wilson (1991) state that AHP provides a substantial advantage to decision-makers by using the pairwise comparison technique. It helps the decision-maker concentrate on comparing only two factors, making the remarks as free as possible from external influences. Harker and Vargas (1987) mention the criticisms about AHP, including lack of axiomatic foundation, the uncertainty of the questions that the decision-maker should reply, and concerns about the scale that is used to specify the level of preferences, address them one by one and show that they are not valid issues when the theoretical background of AHP is taken into consideration. Similarly, a large number of previous works in the literature and numerous academics, companies, and government agencies state that AHP is a trustworthy and useful decision-making method. AHP has been widely used in several areas. Among these, decision analysts, management scientists/operations researchers, and practicing managers have shown high interest in the use of AHP in companies, governmental agencies, and voluntary organizations (Shim, 1989).

The AHP method involves three essential steps: (i) problem is decomposed; (ii) comparative judgment of the alternatives and criteria are made on decomposed steps; (iii) priorities are merged through eigen vectors measuring relative importance (Shim, 1989). According to Saaty (1980), the first step is the determination of the problem and the aim behind the problem. Next, the decision problem is structured as a hierarchy from the top (objectives from the standpoint of the decision-maker) to the intermediate and lowest levels which are composed of criteria and alternatives. The third step of the process is the comparison of decision alternatives and criteria through n x n size pairwise comparison matrices. Each of the lower levels is compared in a comparison matrix regarding the nine-point importance scale. Further details on the steps followed on the application of AHP in this study be found in the works of Dağdeviren *et al.* (2009) and Al-Subhi Al-Harbi (2001).

### 3.3 Integer Linear Programming (ILP)

ILP, which is frequently denoted as Integer Programming, is a specific area of linear programming in which the variables of the problem are restricted to be an integer (Schrijver, 1998). The term linear refers to the linear objective function and linear constraints other than integer constraints. Accordingly, ILP is used to solve optimization problems with discrete or integer variables. Such integer variables are used to model indivisibilities, and binary variables are used to represent decisions to buy, invest, hire, and so on. ILP has the competence to solve numerous assignment, planning, and scheduling problems that frequently occur in daily life (Wolsey, 1998).

Binary Integer Programming (BIP), in other words, zero-one Integer Programming, is an ILP method that all variables are restricted to be zero or one. The assignment problem, 0-1 knapsack problem, set covering problem, traveling salesman problem are primary areas of BIP. Moreover, it is widely used to utilize subcontractor selection decision-making problems in combination with MCDM methods. Talluri (2002) suggested a BIP model rate offers of alternative suppliers based on the optimal goals determined by the buyer. The ratings of alternative offers are evaluated in a BIP model to select an optimal set of offers that satisfies the purchaser's demand requirements. In the end, four different models are built to support the purchaser for a different type of purchasing situations and to provide flexibility for selecting an appropriate method. In another study, Hong *et al.* (2005) have proposed a mixed-integer linear programming model for the supplier selection problem, where the goal of the study was defined as the maximization of the revenue by finding the optimal quantity of the orders and the optimal number of suppliers. A set of constraints were identified, including demand, amount of work, number of selected suppliers, cost, and so forth, whereas integer and non-integer variables were defined to symbolize the values. The authors also considered suppliers' abilities to supply goods and customer requirements over a period of time.

## 4. ANALYSIS

### 4.1 Identification of Criteria Set for Defense Industry Projects

In order to conduct the AHP analysis and to answer RQ1, that is, "What should be the criteria set to evaluate subcontractors for defense industry projects" a detailed literature review has been carried out to determine the criteria set to be used in this study. The studies identified in the literature were applied in different business sectors, e.g., defense, construction, textile, and so on. To specify the criteria related to defense industry projects, several project experts in Company Θ were consulted. Once the criteria set has been identified, a pre-evaluation via semi-structured interviews has been conducted with project managers. These project managers, who may be characterized as decision-makers in defense projects, were asked to grade the importance level of each criterion. The criteria that were greater than or equal to the predetermined cutoff value were chosen for evaluation in the next step.

With respect to a vendor selection problem in the telecommunication industry, Tam and Tummala (2001) have identified 41 criteria that can be grouped into three crucial categories, namely technical success factors, operational success factors, and cost. Al-Subhi Al-Harbi (2001) used AHP to find the optimal ranking of subcontractor candidates and evaluated five companies with respect to six criteria which were equipment resources, financial stability, quality performance, experience, manpower resources, and current works load. Hartmann *et al.* (2009) designed a conjoint experiment to estimate the relative importance level of four criteria: price, technical know-how, cooperation, and quality for the subcontractor selection process in construction projects. The authors implemented a questionnaire about the importance level of four criteria, and price became the most important criterion followed by quality, cooperation, and technical know-how. Belassi and Icmeli Tukel (1996) identified several critical success and failure factors in projects and ranked them for six industry sections, including construction, defense, management information systems, utilities, environmental, and manufacturing. According to the results of a conducted survey, availability of resources was identified as the most important success factor for defense industry projects, and it was followed by project manager's performance, top management support, preliminary estimates, client consultation, and others, respectively. Dağdeviren and Eren (2001) used AHP for selecting a subcontractor and determined quality, supply performance, cost, and technology as selection criteria. They graded these quantitative key features with AHP and came through an evaluation point for each candidate. In the second step, 0-1 Goal Programming was applied with AHP weights and constraints of decision-makers. As the authors stated, if the goal and criteria are identified in consideration of experts and pairwise comparisons matrices are created consistently, the suggested methods can be applied for all business sectors. Kumaraswamy and Matthews (2000) attributed the need for subcontracting in the construction industry and showed that this could be extended further into partnership. Even though eventually they preferred to conduct subcontractor surveys to evaluate the candidates, in the beginning, they worked on criteria set to use during the selection step. Subcontractors' ability to undertake the work, quantity, and standard of work, positive attitude, financial background, in-house design service, management standards, desire to work, price, technical ability, experience, and quality awareness were identified as the critical factors for the evaluation of subcontractor.

Critical factors to be used when evaluating a project do show differences between businesses and industries. It is impossible to specify all critical factors because of this variety of project areas. However, defining an initial group to which these critical factors belong would be helpful to formulate the final solution to be used (Belassi and Icmeli Tukel, 1996). In the identification phase of sub criteria set, criteria data from the literature has been taken into consideration. The subcontractor selection decision-making problem was identified as the key subject, and studies from different sectors of businesses that address the problem of subcontractor selection were reviewed. Once the criteria proposed in the literature were fully assessed, the criteria that were considered suitable and important for defense industry projects were added to the scope of this study. According to the literature on subcontractor selection cases, the selection criteria are grouped into *Corporative Conditions*, *Capabilities of Products*, and *Previous Work Performances*. According to the literature review conducted, twenty-two sub criteria are placed under these three main criteria. Detailed information about which criteria are proposed in which study and the sub criteria determined with expert opinions are given in Table 2. This criteria set also represents the answer to RQ1.

### 4.2 Identified Criteria Set

Moreover, in order to obtain more complete criteria set, a number of criteria were added to the criteria set with the use of expert opinions. In order to collect the opinions of experts, bilateral discussions have been made. These discussions have been conducted with four project managers of Company Θ with experience in the defense industry of 10+, 10+, 8, and 7 years, and experience in project management of 8, 5, 3, and 7 years. The criteria collected by the experts have not been observed in the literature due to the specialization of defense industry conditions. However, they were classified as significant by experienced project managers, as they have recommended that these should be taken into consideration.

***Corporative Conditions***. These factors are based on the socioeconomic characteristics of subcontractor companies and may reflect the current proprietary state of the company or may be characteristics of previous years. Foremost, financial issues, labor-workload conditions, and the business perception of subcontractors are classified as corporative conditions. The sub criteria set under the main criteria of corporative conditions contains private and critical information about the subcontractor companies. Although some of this information may be publicly available, most of them could only be assessed and obtained via interviews conducted with business representatives of the evaluated subcontractor. However, this information may not be reliable to the required extent in such a case. To address this reliability issue, the following actions may be undertaken:

- Gather information from project teams that have ongoing or completed projects with the candidate subcontractor companies.
- Identify for whom the subcontractor has finished products and solicit their comments about the subcontractor company (Assmann and Punter, 2004).
- Ask for detailed and proven company documents.
- Ask for an onsite company visit.

Table 2. Criteria Set from Literature Review and Expert Opinions

| Criteria | Subcriteria | Sources: (Can and Arikan, 2014) | (Al-Subhi Al-Harbi, 2001) | (Tam and Tummala, 2001) | (Narasimhan, 1983) | (Chan and Chan, 2004) | (Birgün Barla, 2003) | (Öztürk *et al.* 2011) | (Hartmann *et al.* 2009) | (Assmann and Punter, 2004) | (Kumaraswamy and Matthews, 2000) | (Chan, 2003) | (Dağdeviren and Eren, 2001) | (Dickson, 1966) | (Sarkar and Mohapatra, 2006) | (Li *et al.* 2006) | ***Expert Opinion*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Corporative Conditions | Financial Stability | | • | • | | | • | | | | • | • | | • | • | • | |
| | Capital Investment | | | • | | | | • | | | | | | | | | |
| | Total Cost | • | | • | • | • | • | • | • | • | • | • | • | • | • | • | |
| | Stability of Key Personnel | | | | | | | | | | | | | | | | • |
| | Human Resources | | • | | • | | | | | | • | • | | | • | • | |
| | Supplier Relations | | | | | | | • | | | | | | | | | |
| | License Rights | | | | | | | | | | | | | | | | • |
| | Corporate Identity | | | | | | | | | | • | | | • | • | | |
| | Current Workload | | • | | | | | | | | • | | | | • | | |
| | Technological Infrastructure | | • | | • | • | • | • | | | | • | • | | • | • | |
| Capabilities of Products | System Reliability | | | • | | • | | | | • | | • | | | • | | |
| | New Feature Capabilities | | | | • | • | | • | | | | • | | | | • | |
| | System Capacity | | | • | | | | | | • | | | | | | | |
| | Interoperability | | | • | | | | | | | | | | | | | |
| | Military Standards | | | | | | | | | | | | | | | | • |
| | System Security | | | • | | | | | | • | | | | | | | |
| | Upgradeability | | | • | | • | | | | | | • | | | | | |
| | Time Lag | | | | | | | | | | | | | | | | • |
| | Ease of Operations | | | • | | | | | | • | | | | | | | |
| | Diversity of Configurations | | | | | | | | | | | | | | | | • |
| Previous Work | Experience | • | • | • | | | | • | | | • | | | | | | |
| | Quality | | • | • | • | • | • | • | • | • | • | • | • | • | • | • | |
| | Logistics | • | | • | | • | | • | | • | | | | • | • | | |
| | Timeliness | • | | | | | • | • | | • | | | | | • | | |
| | Technical Know-How | • | | | • | | • | • | • | • | • | • | | • | • | | |
| | Testing Capabilities | | | | | | | | | • | | | | | | | |
| | Communication | | | | | • | | | • | • | • | • | | • | • | | |

***Capabilities of Products.*** In the subcontractor evaluation, it is a requirement to check the technical sufficiency of pre-designed and completed products with respect to the criteria set developed based on the characteristics of the product that will be produced. Even though a limited number of research consider technical factors about products, these are regarded as highly critical in defense industry projects. Assmann and Punter (2004) assess software subcontractors and implement several selection criteria under two main criteria: evaluation and acceptance. In the sub criteria set of acceptance criterion, they determine product quality as a sub criterion which is composed of software quality and system quality. Reliability, usability, efficiency, maintainability, functionality, performance, effectiveness, portability, satisfaction, safety, and productivity are positioned in the sub criteria set of acceptance. Tam and Tummala (2001) divide the main criteria set for their vendor selection problem into three categories, namely cost, technical factors, and operational factors. Under technical factors, they place technical features, reliability, interoperability with other systems, capacity, upgradeability, redundancy, future technology development, and performance, whereas, under operational factors, they have system security features, fault diagnosis capabilities, ease of operations, performance monitoring capabilities and billing flexibility.

The information to be used when assessing subcontractor candidates with respect to capabilities of products may be collected by following these steps:

- Observe products that are designed and produced by candidate companies in the main contractor's inventory.
- Take end-user feedback about the products that are built partly or completely by subcontractor candidates (Assmann and Punter, 2004).
- Ask for company visits and demonstration of similar products (Assmann and Punter, 2004).

***Previous Work Performances.*** Past performance of the subcontractor candidates should be considered in detail with not only the records in the main contractor itself but also in the sector and customer set (Assmann and Punter, 2004). This part of the criteria set determines experience, quality, logistics, timeliness, technical know-how, and communication as sub criteria. To evaluate the companies with respect to these criteria, records of previous projects should be considered, and the project teams that have worked directly with the company should be interviewed. As the focus of this study is the defense industry, the end-users are mostly military departments. Their opinions about subcontractors and their products should be collected rigorously and evaluated objectively.

## 5. CASE STUDY

The proposed methodology in this study has been applied at Company Θ to show the applicability of the methodology in a real-life setting, with an actual defense industry project and a number of possible subcontractors to be assigned the subparts of the overall project. The details of the decision-making process for choosing subcontractors are demonstrated in the case study for illustrative purposes. The required effort of applying the proposed methodology and the opinions of experts regarding the results and the applicability of the methodology, Tables 8 and 9, respectively, give an important insight for the future use of this approach. Due to confidentiality requirements, the details of the customer, project, product, and four subcontractor candidates (subcontractors X, Y, Z, and W) are only partially disclosed. The conditions and requirements of the case study are summarized as:

- A defense system project has been signed with a customer.
- The project part that will be assigned to subcontractors corresponds to 40% of the total project.
- Due to some reasons (workload, cost issues, offset agreements, etc.), the main contractor wants to assign a part of the project to one or more subcontractors.
- Four existing actual companies are determined as subcontractor candidates, and they are denoted as Company X, Company Y, Company Z, and Company W.
- The main contractor (Company Θ) has worked with all these subcontractor candidates at least once.
- The part of the project which will be assigned to one or more subcontractors is divided into three components as Part A, Part B, and Part C.
- Part A and Part B are found divisible so that Part A is divided into Subpart A1 and Subpart A2 while Part B is divided into Subpart B1, Subpart B2 and Subpart B3. The percentages of each subpart are identified as given below:
  - Subpart A1: 4%
  - Subpart A2: 10%
  - Subpart B1: 8%
  - Subpart B2: 6%
  - Subpart B3: 4%
  - Part C: 8%

- Subparts A1, A2, B1, B2, B3, and Part C are the lowest divisible level of the project part which will be subcontracted.
- These project parts are considered as inside the range of business space for all candidates.

While decomposing the initial project part in the case study into subparts and applying AHP to each subpart, a careful effort of tracking and recording was undertaken to answer RQ2: *"How feasible is to decompose the project into parts and apply AHP for each subpart?"* When the resulting subparts are examined, it is observed that each subpart displays atomic attributes: that is, it consists of its own characteristics and requirements and symbolizes the most divisible structure. However, as the number of subparts increases, the effort needed will increase. The effort required in this case study has been measured as eight-man/hours, and it is given in Table 8.

### 5.1 Preliminary Consideration of the Criteria Set

The criteria set for defense industry projects proposed by this study was determined by examining relative works in the literature and taking into account expert opinions and consists of 27 sub criteria. However, evaluating all 27 sub criteria in the AHP is a challenging task, as using too many criteria increases the number of pairwise comparisons, the decision-making process becomes time-consuming. If there is a high variety between the criteria, it may lead to assessment bias for evaluators (Tam and Tummala, 2001). In addition, using all 27 criteria will probably not provide noticeable results because the weights of criteria will be too close to each other. A preliminary criteria assessment was conducted to reduce the number of criteria to overcome this challenge. A survey was conducted with 12 project managers of Company Θ who were asked to evaluate the importance of each criterion by using a five-point importance scale ("1: not at all important" to "5: very important").

Based on the responses of the survey participants, the criterion of "Military Standards" had the highest level of importance with 4.67 average points, whereas the criterion of "Capital Investments" had the lowest with a 3.25 average point. Tam and Tummala (2001), after conducting a survey to 20 personnel about the importance levels of criteria, have used the cutoff value as the elimination point. In our case, the cutoff value was determined as 3.96 by averaging the lowest and highest mean values. The criteria having mean values less than the cutoff point were eliminated from the evaluation process. Alternatively, the mean of all answers could be used as the cutoff value. In this case, the number of sub criteria would be one less (Current Workload would be eliminated). The initial criteria list and the means of their importance values are given in Figure 3.

Based on the results of the survey conducted with project managers, 11 sub criteria were below the cutoff value. Even though these 11 sub criteria were considered as important by all the decision-makers (as the lowest mean was 3.25 and point 3 was classified as "important") in order to lower the number of sub criteria, all criteria with a mean below the cutoff point of 3.96 were eliminated from the initial criteria set, leaving 16 sub criteria as the Final Criteria Set to be used in the AHP. The Final Criteria Set and the hierarchy of the decision-making problem are given in Figure 4.

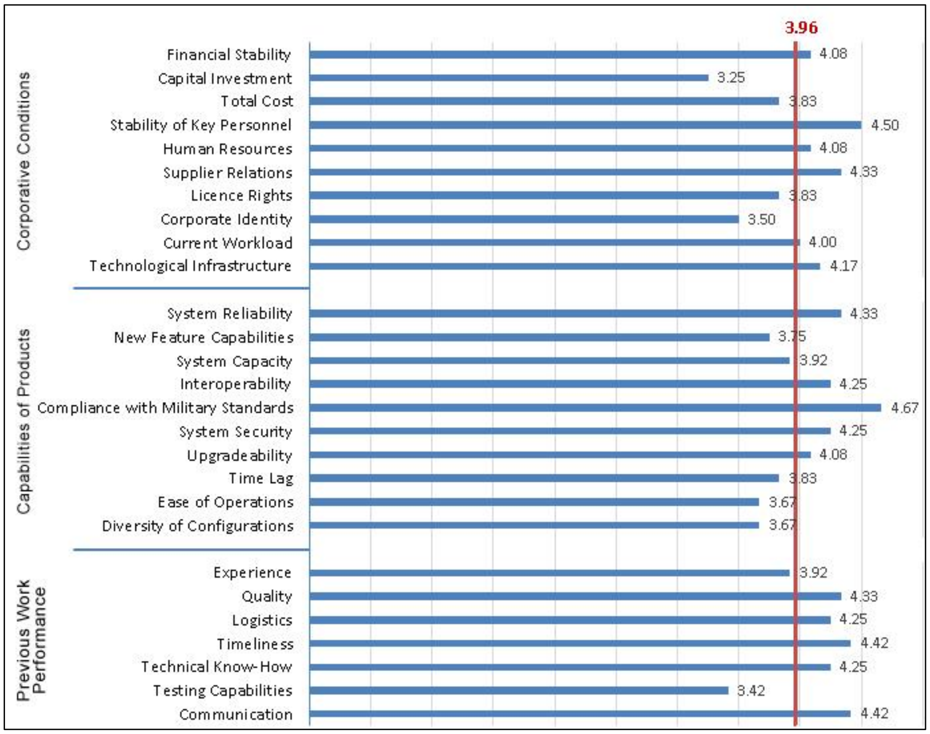


Figure 3. Initial Criteria List and Means of Importance Values

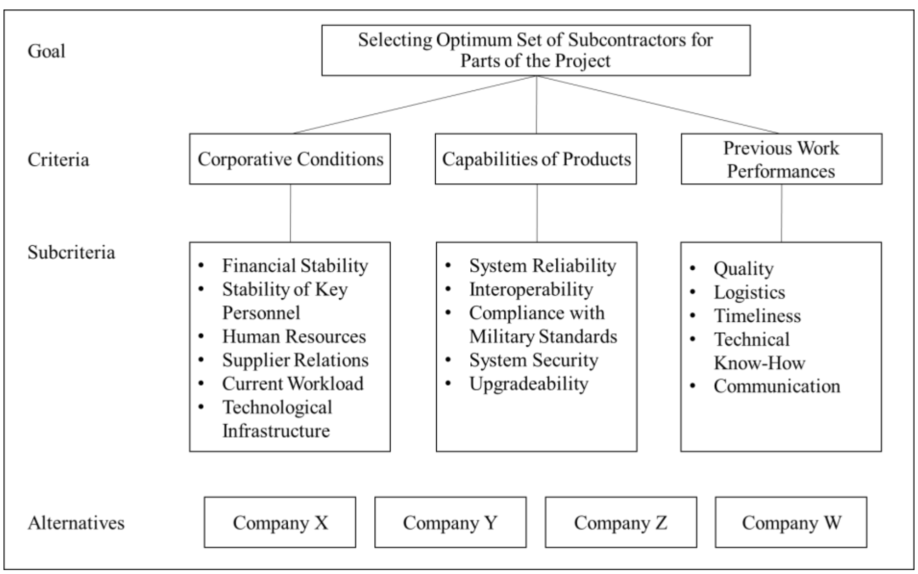


Figure 4. Hierarchy Structure of the AHP Problem

## 5.2 The AHP Model

The AHP model is constructed by following the steps given in the Methodology section. However, before applying the AHP, the criteria set is required to be fine-tuned as not all of the selected 16 sub criteria are related to all project parts. While some of the sub criteria are eligible for all subparts, some of the sub criteria are negligible or unrelated for some subparts. The selected sub criteria for each subpart are summarized in Table 3. Starting with selecting the best subcontractor for Subpart A1, the pairwise comparisons and priority vectors for each subpart are calculated, following the calculation steps defined in AHP.

Table 3. Criteria List According to Subparts of the Project

| | | | Corporative Conditions | | | | | | Capabilities of Products | | | | | Previous Work Performances | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | FS | SKP | HR | SR | CW | TI | SRE | IO | MS | SS | UP | QU | LG | TM | TK | CO |
| Parts | Part A | A1 | • | • | • | | • | | • | | • | • | | • | • | • | • | • |
| | | A2 | • | | • | • | • | | • | | • | • | | • | • | • | • | |
| | Part B | B1 | • | | • | • | • | • | • | • | • | | • | • | • | | • | • |
| | | B2 | | • | • | | • | • | • | • | • | • | • | • | | • | • | • |
| | | B3 | | • | • | • | | • | • | | • | • | • | • | • | • | | • |
| | Part C | | • | | • | • | • | | • | • | | • | • | • | • | • | | • |

FS: Financial Stability SRE: System Reliability QU: Quality
SKP: Stability of Key Personnel IO: Interoperability LG: Logistics
HR: Human Resources MS: Military Standards TM: Timeliness
SR: Supplier Relations SS: System Security TK: Technical Know-How
CW: Current Workload UP: Upgradeability CO: Communication
TI: Technological Infrastructure

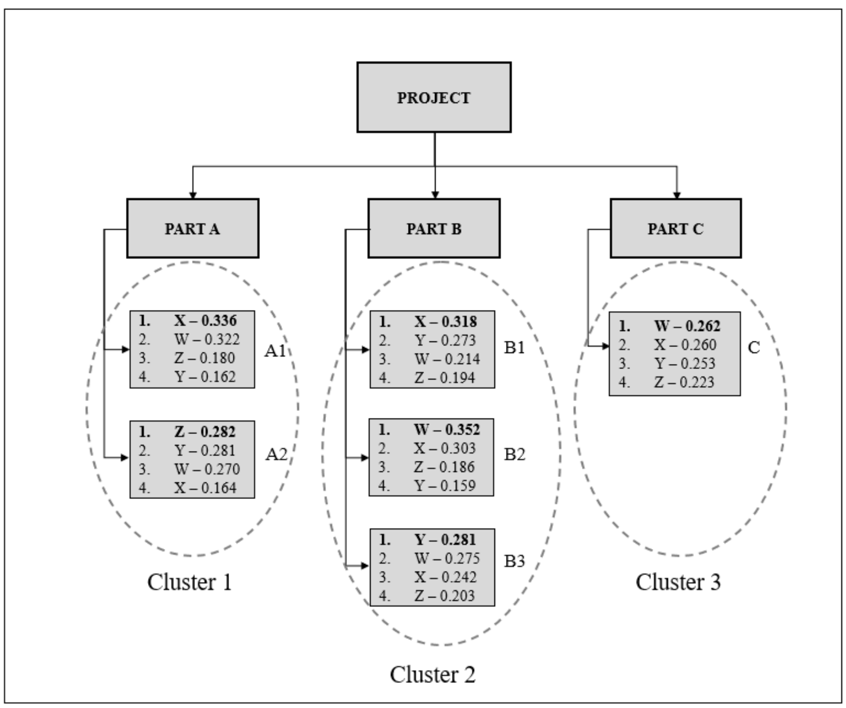


Figure 5. Decomposition of the Case Study Project and AHP Weights of Subcontractors

It is an essential point to control the consistency of the judgments. Therefore, having completed all the pairwise comparisons, the consistency is computed by using the eigenvalue $\lambda_{max}$. As the consistency ratios for all parts found less than or equal to 0.10, rankings and weights of each alternative for Subparts A1, A2, B1, B2, B3, and Part C are given in Figure 5. According to the results, all the alternatives have at least one first rank, whereas subcontractor companies X and W draw attention with two first ranks each. The assignment of subcontractors to each subpart of the project with AHP, as given in Figure 5, is the answer to RQ3. Applying AHP to each subpart instead of the overall project, allowed the decision-maker to employ a different criteria set for each subpart in accordance with the characteristics of that subpart. In this way, not only the most appropriate subcontractor was assigned to each subpart, but also a solution set with ranked weights of subcontractors for each subpart was calculated, thus allowing the decision-maker to assign the subcontractors arbitrarily to these subparts.

### 5.3 Optimization of the Solution

Projects are broken down into work packages to estimate the cost of labor and material in the bidding process with the customer. According to these estimations, each part is assigned a percentage that reveals their comparative size in the overall project. These parts correspond to a percentage of the overall project with respect to the project and subpart cost estimation which are given in Section 5.

Even though AHP provides a ranking of alternatives for each part, it does not take any project constraints into consideration. Defense industry projects generally face contractual, competition, and budgetary constraints. Contractual constraints refer to the contractual clauses regarding industrial participation. When a large-scale contract is signed, the customer may require the main contractor to assign a defined percentage of the project to domestic subcontractors. These conditions may be either a number of subcontractors or a percentage of the total work. However, the main contractor may not want to assign some project parts to some subcontractors in such cases due to rivalry risks. Moreover, working with more than the required number of subcontractors may threaten the position of the main contractor in the sector. To overcome the risks of competition, companies identify several rules for subcontracting. Finally, all projects have a yearly budget that is determined and approved at the beginning of the projects. In the final evaluation of candidate subcontractors, the price factor comes as a limit rather than a factor. In this Case Study, the offers of the candidate subcontractors for each project subpart are given in Table 4.

In this step, in order to evaluate the alternatives with respect to project constraints and limitations, the ILP method is used. The objective function of the ILP problem is determined as "maximizing the total AHP points," and the percentages of each subpart are integrated into the objective function to evaluate the AHP weights with respect to the size of subparts. The constraints of the ILP problem are determined with respect to the following contractual clauses, competition, and budgetary issues.

Table 4. Offers of Subcontractors per Subparts of the Project

| **Cost (in USD)** | **X** | **Y** | **Z** | **W** |
|---|---:|---:|---:|---:|
| Part A1 | 475,000 | 370,000 | 450,000 | 425,000 |
| Part A2 | 1,100,000 | 1,050,000 | 975,000 | 1,200,000 |
| Part B1 | 870,000 | 900,000 | 830,000 | 950,000 |
| Part B2 | 600,000 | 480,000 | 570,000 | 650,000 |
| Part B3 | 425,000 | 390,000 | 420,000 | 465,000 |
| Part C | 1,000,000 | 900,000 | 925,000 | 950,000 |
| **TOTAL** | **4,470,000** | **4,090,000** | **4,170,000** | **4,640,000** |

**Objective Function:** Maximization of the Total AHP Points

**Constraint 1:** At least three subcontractors should be assigned. (Contractual Constraint)

**Constraint 2:** A maximum of 20% of the total project can be assigned to one subcontractor. (Contractual and/or Competitive Constraint)

**Constraint 3:** A subcontractor can undertake subparts of a maximum of two parts. (Competitive Constraint)

**Constraint 4:** A subpart can be assigned to only one subcontractor. (Contractual and/or Competitive Constraint)

**Constraint 5:** The total budget for whole parts of A, B, and C cannot exceed 4,250,000 USD. (Budgetary Constraint)

In order to formulate the ILP constraints, the subparts under the main parts of the project are clustered and are named as shown in Figure 5, starting with one from left to right as their location.

In addition, the following notations are used in the objective function and constraints:

$\mathbf{W_{i,j}}$ : AHP weight of subcontractor i for subpart j
$\boldsymbol{\alpha_j}$ : Percentage of subpart j in total project
$\mathbf{q}$ : Percentage of the project to assign one company
$\mathbf{n_{i,j}}$ : 0 or 1 coefficient (Equals to 1 if subcontractor i is assigned to subpart j)
$\mathbf{c_{i,j}}$ : Cost of assigning subcontractor i with subpart j
$\mathbf{p_k}$ : Number of subparts in cluster k
$\mathbf{mp}$ : Number of main parts to assign one company
$\mathbf{q_k}$ : Overall position of the first subpart in cluster k
$\mathbf{m}$ : Number of alternatives
$\mathbf{t}$ : Number of subparts
$\mathbf{r}$ : Number of clusters
$\mathbf{x}$ : Number of companies assigned
$\mathbf{u}$ : Overall budget for subcontractors
$\mathbf{B_{i,k}}$ : 0 or 1 coefficient (Equals to 1 if subcontractor i is assigned with any subpart in cluster k)
$\mathbf{S_i}$ : 0 or 1 coefficient (Equals to 1 if subcontractor i is assigned with at least one subpart)

The objective function of the ILP problem is to maximize the total AHP weight of the project, where each individual AHP weight is obtained from the assignment of a specific subpart to a specific subcontractor, formulated as:

$$Maximize \sum_{j=1}^{t}\left(\alpha_j * \sum_{i=1}^{m} W_{i,j} n_{i,j}\right) \tag{1}$$

*Subject to,*

Constraint 1:

$$0 \le t\, S_i - \sum_{j=1}^{t} n_{i,j} \le t-1 \quad \forall\, i \tag{2}$$

$$\sum_{i=1}^{m} S_i \ge x_{min} \tag{3}$$

Constraint 2:

$$\sum_{j=1}^{t} \alpha_j\, n_{i,j} \le q_{max} \quad \forall\, i \tag{4}$$

Constraint 3:

$$0 \le p_k\, B_{i,k} - \sum_{j=q_k}^{p_k+q_k-1} n_{i,j} \le p_k - 1 \quad \forall\, i \quad \forall\, k \tag{5}$$

$$\sum_{k=1}^{r} B_{i,k} \le mp_{max} \ \ \forall\, i \tag{6}$$

Constraint 4:

$$\sum_{i=1}^{m} n_{i,j} = 1 \quad \forall\, i \tag{7}$$

Constraint 5:

$$\sum_{i=1}^{m}\sum_{j=1}^{t} c_{i,j} n_{i,j} \leq u \tag{8}$$

where,

$$n_{i,j} = 0 \; or \; 1 \qquad S_i = 0 \; or \; 1 \qquad B_{i,k} = 0 \; or \; 1$$

### 5.4 Results

AHP was selected as the primary method for the solution of the Case Study, whereas project decomposition and ILP have been incorporated to find a more precise result with respect to some prespecified constraints. Lingo 18.0 has been used for the solution of the ILP model. Consistent with the AHP weights, objective function, and constraints, a close set of subcontractor-subpart matchups to AHP results are found. Four of the six subparts are matched with the top priority subcontractors, while two subparts are matched with other than uppermost subcontractors. The comparison of AHP and ILP results is shown in Table 5. The subcontractors that have the highest weights are written in bold. Section 5.3 and the results given in Table 5 constitute our answer to RQ4. With respect to this research question, a set of constraints were identified, these constraints and the objective function were formulated, and finally, ILP was applied to obtain the results of Table 5.

Table 5. Comparison of AHP and ILP Results

| **Alternative / Score** | **A1** | | **A2** | | **B1** | | **B2** | | **B3** | | **C** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AHP | ILP | AHP | ILP | AHP | ILP | AHP | ILP | AHP | ILP | AHP | ILP |
| **X** | **0.336** | | 0.164 | | **0.318** | √ | 0.303 | | 0.242 | | 0.260 | |
| **Y** | 0.162 | | 0.281 | | 0.273 | | 0.159 | | **0.281** | √ | 0.253 | √ |
| **Z** | 0.180 | | **0.282** | √ | 0.194 | | 0.186 | | 0.203 | | 0.223 | |
| **W** | 0.322 | √ | 0.270 | | 0.214 | | **0.352** | √ | 0.275 | | **0.262** | |

### 5.5 Sensitivity Analysis

In order to estimate how sensitive are the results of the calculated AHP weights, a sensitivity analysis has been conducted on each project part. Twelve different cases have been considered where the AHP weight of one of the alternatives has been increased by 5%, 10%, and 20%. The weights of the other three alternatives have been decreased proportionally in each case. According to the change in AHP weights, optimal subcontractor sets are shown in Table 6.

Table 6. Optimal Subcontractor Sets According to the Sensitivity Analysis

| | **Percent Increase** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **5%** | | | | **10%** | | | | **20%** | | | | ***Original Results*** |
| **Company / Subpart** | **X** | **Y** | **Z** | **W** | **X** | **Y** | **Z** | **W** | **X** | **Y** | **Z** | **W** | |
| Part A1 | **X** | W | W | W | **X** | W | W | W | **X** | W | W | W | *W* |
| Part A2 | Z | Z | Z | Z | Z | Z | Z | Z | Z | Z | Z | Z | *Z* |
| Part B1 | X | X | X | X | X | X | X | X | X | **Y** | X | X | *X* |
| Part B2 | **X** | W | W | W | **X** | W | W | W | **X** | W | W | W | *W* |
| Part B3 | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | *Y* |
| Part C | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | **Z** | Y | *Y* |

In the cases of 5% and 10% increase in one of the alternatives, only the increases in the weights of Company X cause a change in the optimal sets. Company X takes the place of Company W for two project subparts which are Subparts A1 and B2, with a slight increase in its weight. This shows us that even Company W seems strong for Subparts A1 and B2. Company X is a very competitive rival for these parts. Another issue to look carefully at is that even there were pretty small differences in AHP weights in some project subparts, especially in Subparts A2, B3, and Part C, the optimal choices for these parts remain the same. This shows that under the current constraints, alternatives are strong candidates for the project subparts they are assigned to. If the increase rate is raised to an upper level, that is 20%, small variations attract the attention differently from the previous rates. Company Y overtakes the place of Company X in Subpart B1 with a 20% increase in its weight, whereas Company Z overtakes the place of Company Y in Part C with a 20% increase in its weight. This signals that there are closely suitable alternatives for Subpart B1 and Part C; however, a considerable change in weights should be constituted according to pairwise comparisons of the decision-makers.

In the documented case study, the budget of the main contractor for the job was defined as 4,250,000 USD. The goal was to reach a combination of subcontractors that gives the maximum AHP point by applying some constraints and being within the project budget. However, the project budget could also be incorporated into the objective function. In this case, the main contractor would be searching the combination of the subcontractors that gives maximum AHP point and requires minimum cost. Starting from 4,000,000 USD, the project budget is increased by 50,000 USD until the AHP point remains constant. This analysis is conducted to demonstrate that alternative solutions may be given to decision-makers if the project budget is flexible within a range. The decision-maker can make a comparison between cost and AHP point and concede a part of AHP point for some cost reduction or vice versa.

The decision-maker can choose to spend an amount between 4,000,000 USD to 4,310,000 USD regarding her/his perception of the sufficiency of the AHP point. As can be seen from Table 7 AHP point increases more sharply in the beginning, then the speed of increase in the AHP point decreases. The maximum AHP point is reached when the budget limit is increased to 4,350,000 USD (with a total cost of 4,310,000 USD), and it remains constant from this point on.

Table 7. Effects of Budget Change on AHP Point and Cost

| Budget (in USD) | AHP Point | AHP Point Increase | Cost (in USD) |
|---|---|---|---|
| 4,000,000 | 1.491 | - | 4,000,000 |
| 4,050,000 | 1.615 | 0.124 | 4,040,000 |
| 4,100,000 | 1.624 | 0.009 | 4,090,000 |
| 4,150,000 | 1.642 | 0.018 | 4,130,000 |
| 4,200,000 | 1.759 | 0.117 | 4,160,000 |
| 4,250,000 | 1.808 | 0.049 | 4,210,000 |
| 4,300,000 | 1.822 | 0.014 | 4,260,000 |
| 4,350,000 | 1.831 | 0.009 | 4,310,000 |
| 4,400,000 | 1.831 | 0.000 | 4,310,000 |

## 6. CONCLUSION

This study has put forward four Research Questions regarding optimal subcontractor selection for defense industry projects through project decomposition and, in accordance, proposes a model for evaluating alternative subcontractors with respect to a wide range of criteria. To address RQ1, criteria set that consists of 27 sub criteria under three main groups have been developed with a detailed literature review and expert opinions. Regarding RQ2, the feasibility of the project decomposition was demonstrated with a case study which was conducted in a defense industry company with a real-life defense project. According to the characteristics of the works in the case study project, the project part was divided into three main parts and six subparts. An important difference from previous studies, and as a contribution of this study, AHP has been applied to subparts of the project instead of using it for the overall project as a proposed answer of RQ3. Weights of sub criteria and alternatives were computed for six subparts separately; therefore, each alternative with the highest weight for each subpart was considered the most suitable alternative according to AHP results. Although we found a solution for each subpart of the project by computing the best alternative using AHP, several constraints should be included in the evaluation process. To find an optimal set of subcontractors, that is, to answer RQ4, ILP has been applied with the objective function of maximizing AHP weights subject to the pre-defined constraints.

Even though this study proposed a new methodology and applied it in a case study from the defense industry, the range of application may be easily expanded to other business sectors in which subcontracting is used intensively as a business approach. In such a case, the identified criteria set may be extended, narrowed, or changed completely in order to be adapted for different sectors. Likewise, new criteria set may be identified for each project subpart instead of choosing convenient sub criteria from the wide list of criteria set. A significant amount of time should be allocated for literature search on different fields of work to find more specific criteria for each subpart. This process might give more exact solutions but also pose a risk of not finding a sufficient number of criteria in an extended period of time.

In the undertaken case study, all alternative subcontractors were determined as capable of undertaking all subparts, so the set of alternatives remained the same for each evaluation. However, suppose the decision-makers think that different subcontractor alternatives are more capable for various subparts or totally inappropriate for other subparts. In that case, a different set of alternatives may be identified for each subpart of the project. It will be more effective in the case of companies that are specialized extensively in different areas of work.

The combined method of project decomposition, AHP, and ILP requires quantifying all the subcontractors for all parts at the same time. The constraints are taken into consideration to reach an aggregate solution in the final phase, which is ILP. In the analysis of the case study, a single decision-maker provided inputs for the evaluation of the sub criteria and the alternatives. This decision-maker is the project manager of the case study project and will make the final decision about subcontractors. As some of the weights of alternatives were found too close to each other, it was decided to reach more reliable and objective results by using more decision-makers and collecting their assessments. However, as the number of decision-makers increases, the effort needed for the AHP computation would increase also. This fact stands for a number of subparts, alternatives, and sub criteria to be evaluated with AHP as well. According to the results, each alternative company has become the most appropriate subcontractor for at least one subpart. Finding such a result independently of the constraint of the minimum number of subcontractors proves the importance of project decomposition in our proposed methodology. This situation indicates that the project part has differences in its breakdown structure, and it should be evaluated in parts to find an optimal set of subcontractors.

ILP may be classified as a method that approves and corrects the results attained by AHP. The pre-defined constraints changed the decisions for two of the six subparts as the second highest AHP weight alternative was selected for Subpart A1 and third highest AHP weight alternative was selected for Part C. If the combination of alternatives that have highest AHP weights satisfied all the constraints, ILP would have given the top priority alternatives as well.

A possible drawback of the proposed methodology may be the involvement of human decision-makers. Even though the criteria set has been developed independently of the alternative companies, the evaluations of the companies are strictly dependent on decision makers' objectivity. Another possible downside of the methodology is its time-consuming mechanism due to the number of steps that are required to arrive at a solution. Although software may easily present solutions of AHP once the pairwise comparisons have been made, the process requires significant labor before the AHP calculations begin. In total, a 72 work hours effort was needed for the overall process. This time is expected to increase if the number of criteria, subparts, alternatives, and decision-makers in the problem increases, but we consider that the effort is worth implementing the process. The fundamental steps and estimated labor hours are given in Table 8. The research questions stated in the introduction have been asked to four project experts in a different way that measures the perceived effectivity of the methodology and results of the case study. The answers of project experts based on the Likert Scale are given in Table 9.

The model developed in this study can be classified as a decision-making strategy that may be used to solve subcontractor selection problems in the real business environment. Senior executives, project managers, project teams, and purchasing departments may benefit from this subcontractor selection methodology in order to find the optimal set of subcontractors for the most appropriate project parts while at the same time taking into consideration different constraints. In future studies, the integration of project decomposition with alternative MCDM techniques, such as PROMETHEE and Goal Programming, and alternative mathematical optimization programs, such as non-linear programming and stochastic programming, may be considered. Conducting comparison studies of the proposed methodology with other approaches within the business environment with real-life projects would provide important insights on the improvement of decision-making processes for subcontractor selection. Moreover, the development of a computer application is an important requirement to shorten the required time to implement the model and integrate a more quantitative perspective to overcome any possible human errors during calculations. Such a computer application would also make it possible to compare the proposed methodology with alternative approaches. An interesting extension of the methodology would be introducing and developing a mathematical model and partitioning technique to generate an optimal number of groups for parts and subparts of the project. Such a mathematical model would also increase the value received from the overall implementation of the proposed model.

Table 8. Estimated Efforts Required for the Steps of the Methodology

| Step | Effort Type | Required Effort |
|---|---|---|
| Identification of the criteria set regarding the business area | Literature Review | 40 work hours |
| | Semi-structured Expert Interviews | |
| Preliminary evaluation of the criteria set | Semi-structured Expert Interviews | 8 work hours |
| | Statistical Analysis | |
| Decomposition of the project into reasonable subparts | Project Analysis | 8 work hours |
| Identification of relative sub criteria for each subpart | Semi-structured Expert Interviews | 4 work hours * # of Subparts |
| Identification of alternatives for each subpart | Meeting with Project Shareholders | 8 work hours * # of Subparts |
| AHP calculations of one decision-maker for each subpart | Semi-structured Expert Interviews | 2 work hours * # of Subparts |
| | Computation via software | |
| Implementation of the optimization model | Modeling the objective function and constraints | 2 work hours |
| | Computation via software | |
| **TOTAL** | | **58 work hours + 14 * # of Subparts** |

Table 9. Expert Opinions about the Results of the Study

| Questions | Fully | Mostly | Somehow | Very Little | Not at All |
|---|---|---|---|---|---|
| **Q1)** Can the identified criteria set important address issues regarding subcontractor selection in the defense industry? | 1 | 3 | | | |
| **Q2)** Do you think is the estimated effort worth applying the methodology to the subcontractor selection process? | | 2 | 2 | | |
| **Q3)** Does the application of AHP to decomposed project parts provide a more effective way to select subcontractors? | 1 | 2 | 1 | | |
| **Q4)** Can the use of combined AHP and ILP methods present reliable results for the subcontractor selection process? | | 3 | 1 | | |

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