A Risk Analysis-Best Worst Method Based Model for Selection of the Most Appropriate Contract Strategy for Onshore Drilling Projects in the Iranian Petroleum Industry

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Abstract: The pre-project planning phase has a significant impact on the achievement of project objectives because during this stage, major decisions including involving contract strategies are made with a high degree of uncertainty. Studies show that the contract type can play a unique role in the achievement of project success. On the other hand, drilling projects can be considered as one of the most critical types of projects in the petroleum industry. In this research, a novel risk based best-worst method (risk-BWM) is proposed for solving the issue of selecting the best contract strategy. A three level methodology was designed; firstly, the risk breakdown structure (RBS) of drilling projects was created in four levels including one heading in level 0, eight main areas of risk in level 1, 34 sub-areas of risk in level 2, and finally, 217 risk items in level 3. Secondly and on the basis of BWM, the weights of risk factors were determined as the selection criteria and consequently the best and the worst criteria were specified. Finally, using pair-wise comparisons between six types of drilling prevalent in contracts, the most appropriate contract type was proposed. The contribution of this study is the development of a generic RBS for drilling projects and application of the risk factors for the first time for the selection of contract type using the BWM method, which has the potential of being adapted for other types of underground projects.

Keywords: contract strategy; risk analysis; drilling projects; BWM; RBS

1. Introduction

Drilling projects are very expensive efforts which provide high quality data or valuable products for all mineral searching operations [1]. They pinpoint and distinguish economic mineralization in nearly every case, which provides the true challenge for all the theories, concepts, and predictions developed in the previous phases of the searching process for prospect recognition and target generation [2]. Drilling technology is a distinctive field in which nearly all production is carried out underground [3]. One of the key phases of the upstream sector of onshore projects is drilling [4]. The upstream sector encompasses all phases of exploration, which include seismology and associated geological research, together with exploratory and descriptive drilling activities [5]. These types of projects require strategic planning to succeed, because many factors in different levels affect this section of the industry [6]. Therefore, the risk management and administration of uncertainties in these projects, for instance through contractual provisions, become more crucial [7]. The high risk of such activities is among the key elements of upstream onshore operations. However, there are no consistent models that define, classify, and prioritize drilling risks. Even though the risk registry is not accessible for drilling activities, there is a good likelihood that these approaches and databases will be kept by major oil firms as

technical expertise. It is therefore essential to define and categorize, initially, the challenges underlying this sensitive and significant part of drilling related risk management. It is important to recognize the risks related to the activity in pre-contractual scenarios in which most of the contributing factors have not still been decided. Also, it is highly important to have an appropriate contract for efficient risk management between the contracting parties. Three main conventional drilling contract approaches have been discussed in this study: daily drilling, footage drilling, and turnkey drilling contracts. The most prevalent traditional drilling techniques in upstream oil reserves are these three types of contracts. Considering incentives as a powerful mechanism for achievement of the project objectives increases the potential contractual alternatives from three to six main strategies. However, the lack of investigations on novel contractual solutions, like smart contracts [8], has strongly hindered the whole industry. Getting a good contract becomes much more essential due to the high costs and time invested in onshore and drilling projects. When stakeholders encounter high expenses and multiple risks in these ventures, the value of a strong contract reveals itself, as it adds greatly to the efficiency of the projects, resolves conflicts, and minimizes disagreements. As such, in this analysis, an effective decision method of contract selection as a structured problem [9,10] is offered after considering the risk factors of the oil and gas drilling activity using the multi-criteria decision approach (BWM: best-worst method). The outcomes enable each corporation to obtain, according to its risk acceptance limit, the levels associated with the suggested method and choose the most effective contract structure. By explaining the roles and responsibilities, this approach will greatly reduce the expenses and time needed to finish a project. In the following sections of this paper, the types of drilling contracts and the risks in this industry are introduced and reviewed, the methodology of the study is described, and the proposed RBS, selection criteria weighting method, and contract selection process for an onshore project is illustrated. Finally, the multi-criteria decision making model for selection of the most appropriate drilling contract based on risk analysis is proposed.

2. Literature Review

2.1. Drilling Contracts

The drilling industry consists of five main markets as illustrated in Figure 1 and the drilling contractor is the central point in this context [6]. The upgrade market is related to maintenance and treatment activities; the secondhand market refers to transactions among contractors to sell and to buy equipment; the scrap market is a section where contractors connect to recycling specialized firms; the newbuilds market refers to the relation between the contractor and other firms willing to buy the contractor company. Although other main decisions including selection of the most qualified sources for the project have a significant impact on project success [11], the contract selection is still considered as the most important stage in the pre-project phase. The types of drilling agreements and the risks in this field are presented and examined below. Also, through considering risk assessments by employing multi-criteria decision-making methods, the most suitable drilling contract is recommended.

Drilling contracts are at the heart of the upstream operational deals. They take different forms and are negotiated to various levels based on the contract value, the level of risk, and the nature of criteria that could be determined by regional forms. The emphasis of this study is on the general conditions of common oil and gas contracts [12]. Three main forms of drilling agreements regulate the drilling of domestic oil and gas wells: footage, day-work, and turnkey. The day-work agreement traditionally is the most frequently used type [6], while in some places or during certain periods, the footage or turnkey based contracts could be utilized [13]. The major alterations between these three primarily relate to whether the risk is estimated and apportioned or not [14]. The incentive mechanisms can be combined to each of the above three contracts and on this basis, the possible forms of agreement increase to six alternatives. However, the incentive contractual mechanisms are described below separately.
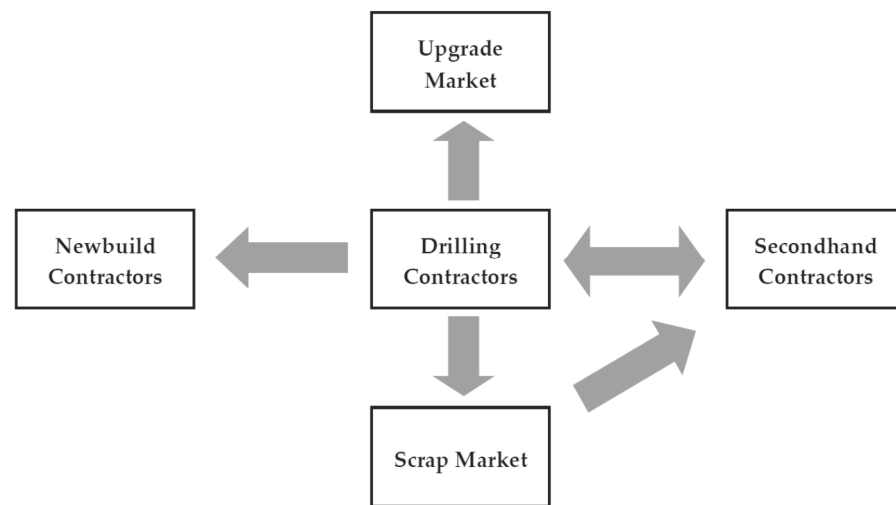
Figure 1. The five main markets of the drilling industry [6].

2.1.1. Day-Rate Contracts

Among drilling agreements, one of them is the "day-rate" or "day-work" [15], which is by far the most functional and the most common type of drilling contracts [1]. Here, the contractor shall be charged a set amount (rate) for work produced by the drilling party over a full-day, with the contractor only accepting defined risks and the drilling party having most of the liabilities [13,16]. The sum of the specified day-rate depends on a variety of factors, like market conditions, the kind of rig, the number of people in the workforce and the team in charge of furnishing the workforce, the stage of operation, the specialization of the operation, the drill pipe, other machinery, and special services. The day-rate can vary at different points of project execution. Moreover, a day-rate contract can allow for lump-sum payments for specialized tasks, including deployment and layoffs [13,14]. Day-work contracts that are commonly used for drilling wells do not create a possibility for the contractor to make profits that could lead to a rise in efficiency or a reduction in well expenses [17]. Day charges operate on demand and supply dynamics in a way that, when demand for a rig goes beyond supply, day rates increase [11,18]. When demand for rigs, particularly those built for a specific purpose, like drilling of a deeper well is at its peak, the drilling operator might ask for a "term day-work" agreement. Within this form of contract, the provider is allowed to expect, for the duration of the contract, a certain day-rate, whether or not the rig is working, standing, or rigged and inactive [13]. A detailed drilling service is provided by the well operator to guide the contractor on how to move ahead with the well, including all the well supplies and any service needed for the well. To mine the well, the drilling contractor supplies drilling tools and staff [19]. Providers have a delegate at the project location. Like management at the rig, the payment system is basically a provider process [16]. Day-work contracts offer a degree of leeway for the provider to modify the work order. At the same time, the contractor would not be given a motivation plan to finish the job more efficiently and at a low cost. Thus, opposed to the primary estimate, there seems to be an inclination to raise costs and time [20]. The drilling party is accountable for the defined risks under the day-rate contract, whereas the provider is accountable for the overall risk of delay or even for the risk of liability not borne by the contractor [13]. In such a deal, the contractor is just responsible for the risks of the machinery, services offered, and the supply of the workforce. All the remaining risks rest on the operator [3].

2.1.2. Footage Contracts

The footage drilling agreement is used in places where drilling expenses can be efficiently anticipated in onshore regions where multiple wells are drilled [21]. A footage contract offers the fixed price per foot for the hole drilled from the ground to the maximum

depth or for any other task required to be paid to the drilling contractor [13]. Essentially, a "footage" contract stipulates that the drilling service provider supplies the drilling staff, the equipment, and certain defined services as well. In a footage contract, the provider undertakes more well-related risk compared to a day-rate contract that is adjusted by a slightly higher price to the operator. The value of such a deal increases if the contractor can drill more effectively than expected. However, if the well faces problems and requires more for each well drilled per foot, then the drilling party pays the extra cost and can lose money [14]. Since the drilling party is compensated just for footage drilled and the specified day-rate, and since it takes on more risk, a footage agreement is considered to be more beneficial to the operator compared to a day-work agreement [13]. Footage deals are mostly considered for the area above the potential reservoir where, from an assessment or processing perspective, hole factors are less important [4].

2.1.3. Turnkey Contracts

A "turnkey" agreement allows for a fixed price to be given to the drilling party to drill a well to a required depth or identified formation [13]. This price concerns the supply by the drilling party of all services, such as the workforce, drilling rigs, machinery, equipment, and particular services. Once the operation is completed, the negotiated amount can be reimbursed and the well is dug to a specific depth (Contract Depth) [22]. The complication with this plan is making sure that the company is provided with a "quality well" because the drilling party wants to dig as quickly and frugally as possible. Thus, for each well, the drilling party should ensure there is an agreed objective quality level. The assurance must determine remedial steps to be carried out if a substandard well is delivered [4]. For the drilling party, a pure turnkey agreement offers the highest risk as well as the highest reward. With this type of agreement, for a lumpsum, set price, a drilling contractor is obliged to drill the well completely. The drilling contractor covers all the expenses and risks of the work and makes contracts for machinery and services with third parties. Therefore, to minimize the risk ingrained in drilling wells, operators choose turnkey contracts [14]. Since the drilling party assumes all risks, the actual anticipation of the "cost" of the well must be increased to reduce such risks. The potential cost of these risks is applied to the projected real cost, and the profit margin, to achieve a turnkey bid price [21].

2.1.4. Incentive Contracts

Conventionally, incentive agreements (sometimes referred to as "risk contracts") are based on footage or turnkey ideas in the drilling sector [23]. Today, however, despite the form of agreement used, steps have been taken to guarantee that the arrangement between the parties provides motivations in line with the conditions of each contract. Incentive agreements are a way of forming a connection between the sums charged and the efficacy of the services provided by the operator. In this type of contracts, objectives are established based on capability standards. The costs of services are then changed based on the achievement of the intended targets. The productivity-based price change is an efficient way to attract contractors. Therefore, accomplishing the drilling objectives results in rewarding the contractor, and failure to deliver them will lead to a fine [24]. Recently, this approach of engaging in drilling activities has been implemented very efficiently and has led to a considerable reduction in expenses. Different systems are in deployment, generally offering a bonus for greater productivity than average. The contractor is in accord with the company on the requirements for the well. Thus, the 'historic' cost is delineated for similar wells that have been drilled already. This enables the projected cost of the new well to be calculated. The drilling party will be solely responsible for digging the well, and the company and the contractor will divide the cost savings obtained.

2.2. Risk Analysis of Drilling Projects

Risk can be defined in various ways. The established outlooks and meanings of risk are centered on probabilities [25]. PMBOK (2018) describes risk as any "uncertain

event or condition that, if it occurs, has a positive or negative effect, such as time, cost, scope or quality, on at least one project objective." Wideman (1992) describes project risk as "the cumulative effect of the chances of uncertainty occurrences adversely affecting project objectives" [26]. Some more risk definitions are as follows: Risk is a way of measuring the possibility and severity of undesirable reactions [27]; Risk is a combination of the possibility of a situation and its repercussions [28]. As long as they are in step with the benefits, certain risks should be considered. Risks pose threats to the progress of ventures. It has been shown that failure to properly manage risks causes time and cost overruns in activities [29]. For all these concepts, what is similar is that events (initiating incidents, scenarios), consequences (results), and probabilities are included in the definition of risk. Uncertainties are stated through probabilities [25]. It is worth mentioning that there are theoretical differences between application of the risk and the uncertainty concepts; whereas risk refers to circumstances where the possible consequences and their probabilities are determinable for the decision-maker, uncertainty is used for situations that the probability and impact of occurrences are completely unknown [30,31].

2.2.1. Risks of Contract

The term 'risk allocation' is widely used to define responsibilities. The distribution of responsibilities among each of the parties to the contract is a basic component of contract terms. There is a hypothesis that responsibilities should be assigned based on who is in the right position to manage risks or for whom those risks are economically feasible. It may be argued that the exercise of obligation distribution should be done in the most balanced way. It seems that the client should assume those liabilities and risks, which really are under the command of the client and the contractor should assume the liabilities and risks that are under the command of the contractor.

2.2.2. Risk Management in Drilling Process

Drilling is a strategic and vital activity, featuring practices that are dynamic and dangerous in resource exploration [32]. A danger is any unscheduled event (risk) or incident likely to cause a drilling process to diverge from its predefined strategy or critical path [33]. These unplanned incidents give rise to events ranging from unproductive drilling time or marginal impacts on the drilling (small amounts of fluid wasted) to serious wellbore malfunctions and a lack of command in the drilling process. It is also described as "trouble." Not only geological uncertainty, but also mechanical issues or human errors are the results of these incidents. Finally, the drilling schedule, budget, project completion, and credibility of the companies concerned will be impacted by these disruptions [34]. More updated information surfaces when the drilling starts and some expected hazards may still cause harm, whereas others may not. It is possible to discover and identify new hazardous situations, and the nature of those that are already known may change. Risk management should also be planned out at all levels of the project regularly, that is before, during, or after drilling [35]. Of the most significant elements of setting up subsurface geology in engineering projects is the management of drilling hazards. Drilling risks resulting from geological uncertainties, technical problems, environmental extremes [36,37], or human error have been reported at coastal and terrestrial sites [33]. A Risk management process includes the procedures for the preparation, assessment, review, response planning, implementation of responses, and control of the risk of the work [38]. The primary goal is to define and monitor the most relevant risks [39]. The most critical hazards in the drilling sector must therefore be identified [29]. Either internal or external risks threaten drilling programs. All the risks could hurt the project's budget, schedule, or efficiency. Risk management should therefore be well understood and managed as an interconnected project management feature [40].

3. Research Methodology

To achieve the research's objectives including: 1. Recognition of the main risks of drilling projects in Iranian onshore oil fields, 2. Ranking identified risks, and 3. Selection of the most appropriate drilling contract based on risk analysis, a three levels methodology was created. In the first step, to recognize the uncertainties and challenges of drilling projects in a hierarchical manner, a questionnaire was designed in a closed format. In this questionnaire, data relating to risks in drilling projects were gathered and subsequently organized into a proposed structure. The experts were asked to add, amend, or delete items as required, reaching consensus among experts towards the end of the process. The input of the first stage was a basic structured data of disputes extracted from the literature review and the output was the risk breakdown structure (RBS) of drilling projects. We explained that in reviewing the available resources, the researchers were looking for items that have been introduced in previous references as possible and probable risk parameters affecting drilling projects that, if they occur, affect one of the predetermined objectives. These sources are listed in the presented table in the Appendix A. The second questionnaire was designed to obtain the experts' judgments about the risks occurrence probability and their prospective impact on the project objectives. The key project objectives including cost, time, quality, environment, and safety were adopted in this regard. The input of this stage was the RBS and the output was the estimation of probability and impact assessment of the recognized risks. On the basis of the above quantitative analysis using the opinion of the experts, 35 of the most effective risks were selected for applying in a project contract strategy selection model. Finally, the experts were asked to assess the appropriateness of contract alternatives against the selected risks, and then the most appropriate contract strategy was proposed based on the BWM method. Since there is no reliable database which has organized and has assessed the risks of drilling projects, acquiring the experts' opinions was considered as the most reliable method and therefore all above data gathering procedures were programmed in a Delphi process. In this regard, a two round Delphi technique (for each stage) with a panel including eight experts who had one of the following three characteristics were considered:

- At least eight years' experience in management of drilling contracts; or
- At least 10 years' experience in academic research on drilling contracts; or
- At least having a master's degree in petroleum project management.
- The research methodology and its elements are shown in Figure 2.
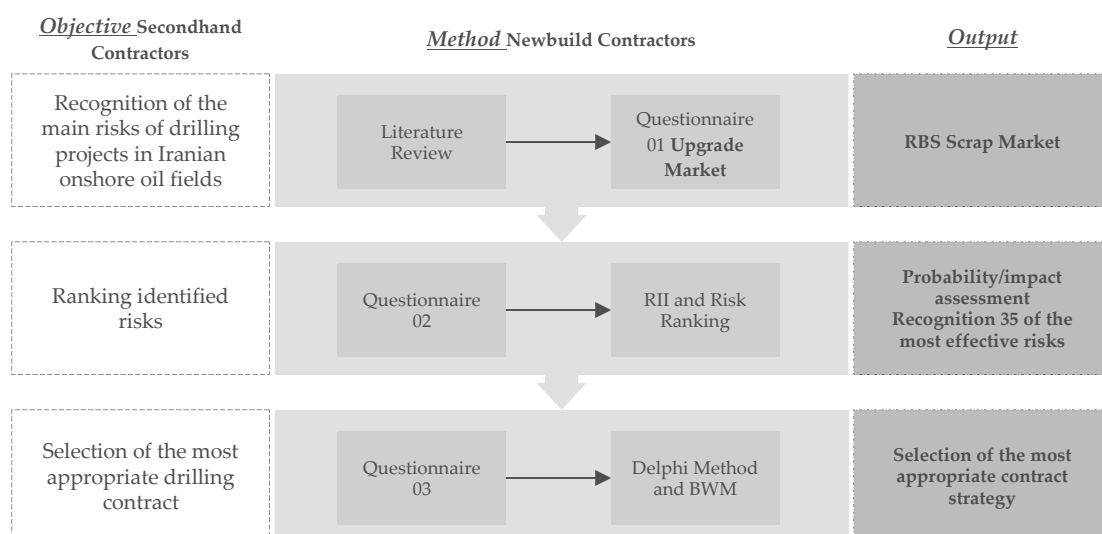
Figure 2. Objectives, methods, and outputs in each stage of the research methodology.

The Best Worst Method (BWM) is a multi-criteria decision-making method developed by Jafar Rezaei [41]. In order to identify the weights of parameters, BWM utilizes two sets of pairwise comparisons. It contrasts the best parameter with the other parameters and the worst parameter with all the other parameters. The objective was to find the optimum proportion of weights and consistency by means of a standard linear optimization model developed by a comparative system [42]. The BWM previously has been applied in a vast spectrum of research in the construction area such as the supplier selection [43–45], the contractor selection [46,47], site selection [48,49], and risk assessment [50,51]. Previous investigations demonstrate that the BWM method can lead to more consistent pair-wise comparisons and outcomes with higher reliability than conventional approaches. The Analytical Hierarchy Process (AHP) could be known as a multi decision-making strategy that can incorporate qualitative and quantitative variables in the overall assessment of alternatives [52,53]. It comprises three sections: the hierarchical structure, the pairwise comparative matrix, and the priority calculation method. The AHP evaluates the priority of any alternative to the overall objective of the issue of concern. At the peak of the hierarchy lies the ultimate target or the main objective. Subsequent lower levels then reflect a progressive dissolution of the alternatives to the problem. A decision-maker or a qualified party will perform a pairwise analysis of all the items at each point related to each of the project items at the higher step of the hierarchy. The pairwise analysis is founded on a range of 1–9, as described in Table 1 [54]. The formation of these decisions sets the criticality of the items at the lowest point (generally solution alternates) related to the achievement of the highest objective [53].

Table 1. The comparison scale of the Analytical Hierarchy Process (AHP) method.

Weight	Definition
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments
Reciprocals of previous values	If factor "*i*" has one of the previously mentioned numbers assigned to it when compared to factor "*j*," then *j* has the reciprocal value when compared with *i*

4. Data Analysis and Results

4.1. Risk Analysis to Develop the Selection Criteria

As discussed earlier, due to the lack of a coherent database of risks of drilling projects, despite the experience of hundreds of drilling projects in Iran and even a lack of access to such a bank internationally, the risks were first identified using the study of previous research and available technical documents. However, overall 217 risks were recognized: 122 items from the literature review and 95 items from the first stage of the methodology, including two rounds of the Delphi method. Therefore, in this process, a comprehensive list of potential risks of drilling contracts was formed and at the same time a categorizing procedure for rolling up the risks in a class was done. Thus, the output of this stage was the risk breakdown structure (RBS) of drilling projects of the petroleum industry as a generic list of potential uncertainties. The proposed RBS consists of one heading in level 0, eight main areas of risk in level 1, 34 sub-areas of risk in level 2, and finally 217 risk items in level 3. The comprehensive list of recognized risks in the form of RBS of drilling projects is shown in Appendix A. Figure 3 illustrates the four levels of the risk structure for organizational risks and organization related items.
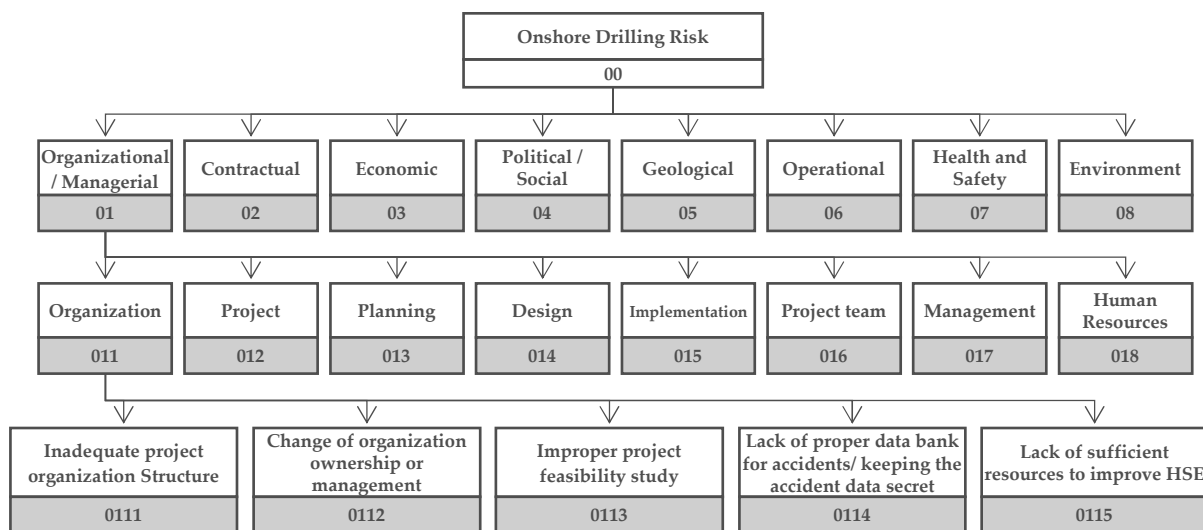
Figure 3. Hierarchical view of the proposed risk breakdown structure (RBS) for drilling projects (level 0, 1, 2, and 3 of branch 01).

Obviously, the importance of the recognized risks is not equal for all drilling projects and therefore, it was essential to rank them and to focus on the most effective items. In order to examine the prioritizing procedure of the potential risks, a real drilling project with the following eight features was selected:

1. Onshore project
2. Oil field with about 10 years production (brown field)
3. Sandstone formation with low porosity
4. Homogeneous formation without fracture
5. Drilling depth up to 100 m
6. Vertical drilling method
7. Available data of previous well drillings
8. Conventional access to the well drilling location.

Based on the experts' opinions, the probability of risk occurrence and also their impacts on objectives of the defined project have been judged. Using the average of gathered data, the risk importance index (RII) was calculated based on the Equation (1):

$$RII_{Ri} = \frac{1}{5} \sum_{j=1}^{5} P_i I_{kj} \tag{1}$$

where RII_{Ri} indicates the risk importance index of risk Ri on project objective k, $k \in$ {cost,time,quality,environment,safety}, P_i is the probability of occurrence of Ri and I_{kj} is the impact of risk Ri on the project objective k. The higher value of RII presents an overall risk significance in the project parameters. Table 2 represents the top ranked risk importance index of drilling projects' risks and impact of them on the five main project objectives including the cost, time, quality, safety, and environment. The cutting line for top risks was determined to be the minimum overall impact of 0.4 on project objectives based on the 35 high risks that have been identified. It should be mentioned that the cutting point have been applied on each of eight main areas, in order to build a more balanced list of high risks. Also, Table 3 summarizes the top 10 ranked risks which have the most impact on a specified project objective. Figure 4a shows the overall top ten most effective risks and Figures 4b, 5 and 6 demonstrate this index per each project objective.

Table 2. The list of risks with the highest RII.

Risk Code	Description of Risk	RBS Code	Probability	Impacts on Project Objectives					RII
				Cost	Time	Quality	Environment	Safety	
R1	Blow out of project contingency	6601	0.55	5.206	4.250	4.327	3.331	4.082	4.239
R2	Tight hole of the well and casing run problems	6109	0.42	3.198	2.753	2.808	2.474	2.939	2.834
R3	Pipe failure	6201	0.45	3.805	4.418	3.156	0.953	1.702	2.807
R4	Changes in the size of the inner diameter of the casing in some parts due to impact	6106	0.42	3.736	3.877	2.700	1.907	1.421	2.728
R5	Lack of well rehabilitation before casing running operations and the resulting problems	6101	0.45	3.988	3.602	3.233	1.349	1.400	2.714
R6	Collapsing formation and wellbore instability	6701	0.45	3.640	3.961	3.444	0.362	0.971	2.476
R7	Poor design and late changes to well design and procedures	1403	0.46	4.108	4.875	2.830	0.124	0.241	2.436
R8	Loss of circulation	6401	0.42	3.678	3.033	3.055	0.069	0.940	2.155
R9	Sanctions and special bans	4205	0.35	2.235	2.547	1.660	0.852	2.782	2.015
R10	Incompetence of project team	1601	0.35	3.598	2.806	3.104	0.133	0.111	1.951
R11	Equipment failure	6809	0.35	2.262	2.764	2.681	0.707	1.337	1.950
R12	Blocking of the drilling pipe or product pipe installation due to the swelling of clay and silt	6208	0.39	3.663	3.274	2.344	0.237	0.173	1.938
R13	Exchange rate changes	3104	0.35	2.495	2.997	2.038	0.733	1.154	1.883
R14	Weakness in planning and scheduling and initial project resources	1301	0.31	2.095	1.998	2.215	1.480	1.525	1.863
R15	Infiltration of drilling mud into wells	6501	0.32	2.498	2.607	1.575	0.800	0.467	1.589
R16	Excessive delays due to late decisions making by project participants	1606	0.31	2.413	2.704	1.071	0.481	0.781	1.490
R17	Problems in casing cementing and Staying cement in casing	6303	0.25	1.653	1.675	1.325	0.825	0.691	1.234
R18	Ambiguous conditions of contract	2102	0.25	1.520	1.878	1.183	0.612	0.693	1.177
R19	Inappropriate choice of project implementation method	1501	0.21	1.129	1.409	1.383	0.306	1.152	1.076
R20	Corrosion or wear of mechanical parts	6801	0.25	1.953	1.447	0.981	0.157	0.472	1.002
R21	Error in measuring the correct weight of cement	6308	0.23	1.445	1.323	1.269	0.625	0.290	0.990
R22	Lack of skills of drilling staff (inadequate practice of skills)	1801	0.23	1.426	1.199	1.196	0.515	0.567	0.981

Table 2. *Cont.*

| Risk Code | Description of Risk | RBS Code | Probability | Impacts on Project Objectives | | | | | RII |
				Cost	Time	Quality	Environment	Safety	
R23	Work conditions deferring from contract	2104	0.16	1.127	1.294	0.851	0.443	0.753	0.894
R24	Change in rules and regulations	4107	0.22	1.486	1.538	0.759	0.270	0.115	0.834
R25	Improper cost calculations for the investment	3203	0.15	0.818	0.707	0.715	1.052	0.834	0.825
R26	Inadequate project organization structure	1101	0.21	1.590	1.059	0.652	0.089	0.545	0.787
R27	Unclear and imprecise delegation of responsibilities and roles and project charter	1203	0.16	1.001	0.891	0.612	0.615	0.792	0.782
R28	Change of organization ownership or management	1102	0.22	1.105	1.163	0.847	0.036	0.547	0.739
R29	Acidizing which causes cracking of lines and hitting people, acid spraying and severe acid burns	7104	0.18	1.083	1.050	0.947	0.056	0.460	0.719
R30	New and complex technology (e.g., packers and liner hangers)	6901	0.16	0.992	1.104	0.650	0.105	0.627	0.696
R31	Geological structure and complexity of the region	5101	0.15	1.011	0.811	1.035	0.118	0.107	0.616
R32	Oil and gas leaks, toxic gas leaks, waste, or other environmental pollutants	8501	0.14	1.026	0.929	0.383	0.281	0.460	0.616
R33	Disposal and discharge of wastewater and drilling fluid	8301	0.15	0.730	0.144	0.057	1.213	0.037	0.436
R34	Lack of sufficient knowledge and information of field and reservoir structures	5202	0.15	0.766	0.067	0.010	1.230	0.072	0.429
R35	Changing social responsibility rules and regulations	4303	0.14	0.440	0.653	0.485	0.115	0.336	0.406

Table 3. The top risks versus each objective of the drilling project.

Project Objective	Risk Code	Description of the Risk	RII
Cost	R1	Blow out of project contingency	5.206
	R7	Poor design and late changes to well design and procedures	4.108
	R5	Pipe failure	3.988
	R3	Tight hole of the well and casing run problems	3.805
	R4	Loss of circulation	3.736
	R8	Lack of well rehabilitation before casing running operations and the resulting problems	3.678
	R12	Sanctions and special bans	3.663
	R6	Changes in the size of the inner diameter of the casing in some parts due to impact	3.640
	R10	Exchange rate changes	3.598
	R2	Collapsing formation and wellbore instability	3.198

Table 3. *Cont.*

| Project Objective	Risk Code	Description of the Risk	RII
Time	R7	Poor design and late changes to well design and procedures	4.875
	R3	Tight hole of the well and casing run problems	4.418
	R1	Blow out of project contingency	4.250
	R6	Changes in the size of the inner diameter of the casing in some parts due to impact	3.961
	R4	Loss of circulation	3.877
	R5	Pipe failure	3.602
	R12	Sanctions and special bans	3.274
	R8	Lack of well rehabilitation before casing running operations and the resulting problems	3.033
	R13	Blocking of the drilling pipe or product pipe installation due to the swelling of clay and silt	2.997
	R10	Exchange rate changes	2.806
Quality	R1	Blow out contingency	4.327
	R6	Changes in the size of the inner diameter of the casing in some parts due to impact	3.444
	R5	Pipe failure	3.233
	R3	Tight hole of the well and casing run problems	3.156
	R10	Exchange rate changes	3.104
	R8	Lack of well rehabilitation before casing running operations and the resulting problems	3.055
	R7	Poor design and late changes to well design and procedures	2.830
	R2	Collapsing formation and wellbore instability	2.808
	R4	Loss of circulation	2.700
	R11	Incompetence of project team	2.681
Environment	R1	Blow out contingency	3.331
	R2	Collapsing formation and wellbore instability	2.474
	R4	Loss of circulation	1.907
	R14	Infiltration of drilling mud into wells	1.480
	R5	Pipe failure	1.349
	R34	Disposal and discharge of wastewater and drilling fluid	1.230
	R33	Oil and gas leaks, toxic gas leaks, waste, or other environmental pollutants	1.213
	R25	Acidizing which causes cracking of lines and hitting people, acid spraying, and severe acid burns	1.052
	R3	Tight hole of the well and casing run problems	0.953
	R9	Equipment Failure	0.852
Safety	R1	Blow out contingency	4.082
	R2	Collapsing formation and wellbore instability	2.939
	R9	Equipment Failure	2.782
	R3	Tight hole of the well and casing run problems	1.702
	R14	Infiltration of drilling mud into wells	1.525
	R4	Loss of circulation	1.421
	R5	Pipe failure	1.400
	R11	Incompetence of project team	1.337
	R13	Blocking of the drilling pipe or product pipe installation due to the swelling of clay and silt	1.154
	R19	Lack of skills of drilling staff (inadequate practice of skills)	1.152
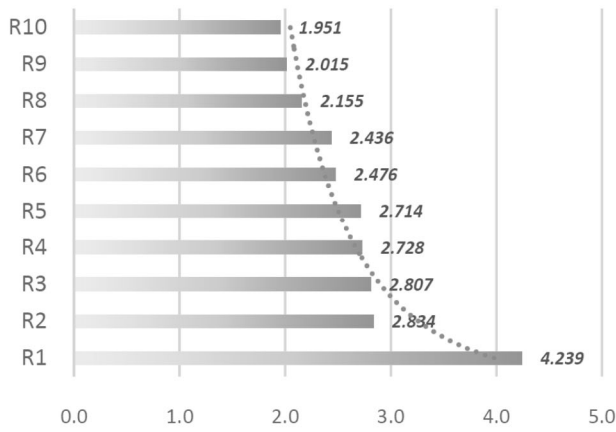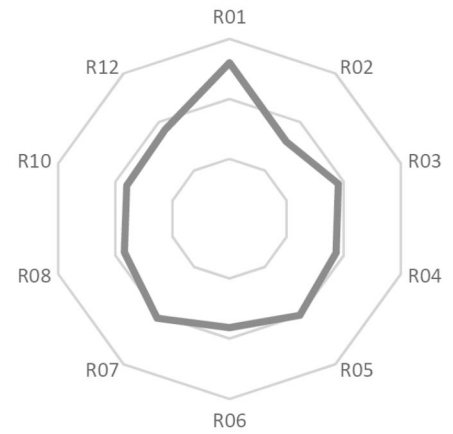
Figure 4. (**a**) Overall top 19 most effective risks, (**b**) Top 10 risks for cost objective.
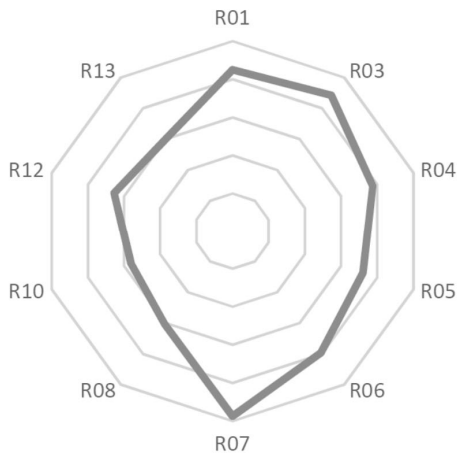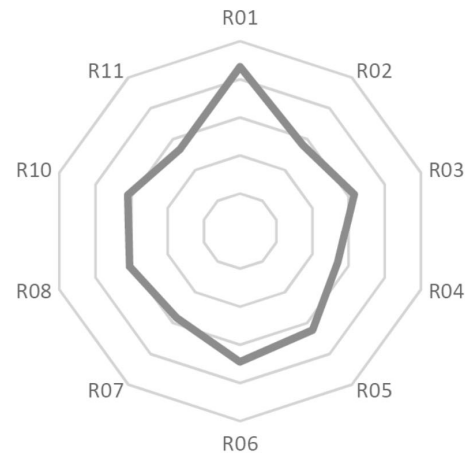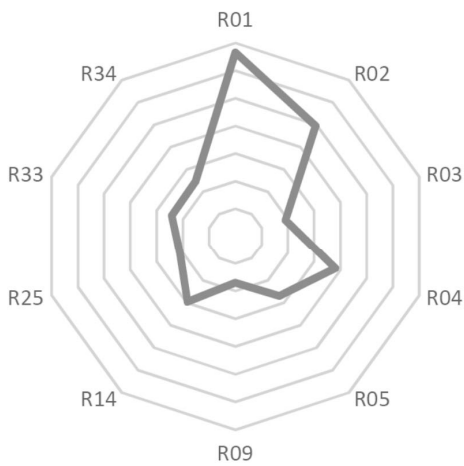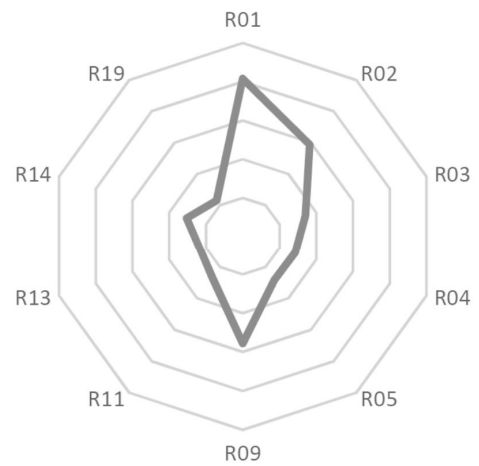

Figure 5. (**a**) Top 10 risks for time objective, (**b**) Top 10 risks for quality objective.

Figure 6. (**a**) Top 10 risks for environment objective, (**b**) Top 10 risks for for safety objective.

4.2. Weighting of Identified Drilling Risks Using BWM Method

In the next step and to calculate the weight of each risk on project contract selection the BWM was adapted from [55] and was employed in accordance with the following procedure:

1. Considering the high importance risks as the set of decision criteria $\{R_1, R_2, \ldots, R_n\}$ by decision-makers.

2. Determining the best and the worst criteria to be used for the decision environment. This step generally is done by choosing the best and the worst criteria among the set of criteria identified in Step 1 from the perspective of decision-makers. The best criteria represent the most important criteria and the worst criteria are the least important criteria for the decision. This step in the current study has been completed in the previous stage and the importance of the criteria has been determined already. The Blow out contingency (R1) and the Changing social responsibility rules and regulations (R35) have been considered as the best criterion and the worst criterion, respectively.

3. Determining the preference of the best criteria over all the other criteria: A number between 1 and 9 (1: equally important, 9: extremely more important) is used to indicate this value. The resulting Best-to-Others vector would be as $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$, where a_{Bj} indicates the preference of criteria B (best criteria) over criteria j and $a_{BB} = 1$. Using the BWM questionnaire, experts were asked to compare R1 with each of the other criteria and to express their preference using a value between 1 and 9. Then, by calculating the geometric mean of the four questionnaires, aggregated Best-to-Others (BO) was constructed, as shown in Table 4.

4. Determining the preference of each of the other criteria over the worst criteria: A number between 1 and 9 was assigned to this case as well. The Others-to-Worst vector would be $A_w = (a_{1w}, a_{2w}, \ldots, a_{nw})^T$, where a_{jw} indicates the preference of the criteria j over the worst criteria W and $a_{ww} = 1$. Similarly to the previous step, the experts were then asked to express their preferences of all other criteria over the least important criterion of R35. As in the previous step, a value between 1 and 9 was used to determine the preferences. Then, by calculating the geometric mean, the aggregated Others-to-Worst (OW) vector was constructed as shown in Table 5.

5. Find the optimal weights $(w_1^*, w_2^*, \ldots, w_n^*)$: Solving the problem (1) will result in the optimal weights for the criteria. To determine the optimal weights of the criteria, the maximum absolute differences $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_w} - a_{jw}\right|$ for all j should be minimized.

$$\mathrm{minmax}_j \left\{ \left|\frac{w_B}{w_j} - a_{Bj}\right|, \left|\frac{w_j}{w_w} - a_{jw}\right| \right\}$$
$$\text{s.t.}$$
$$\sum_j w_j = 1$$
$$w_j \geq 1, \; for \; all \; j$$

Table 4. Criteria Best-to-Others (BO) Vector.

Best Criterion.	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24	R25	R26	R27	R28	R29	R30	R31	R32	R33	R34	R35
R1	7	8	7	5	3	6	4	5	6	5.7	6.6	4.3	6.9	6.7	3.6	8.8	8.2	8.7	2.5	2.2	1.9	2.1	4.2	5.4	6.2	3.3	4.9	1	2.8	6	3.9	7.9	7.8	8.5	8.4

Table 5. Criteria for Others-to-Worst (OW) Vector.

Worst Criterion.	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24	R25	R26	R27	R28	R29	R30	R31	R32	R33	R34	R35
R35	3.8	3.5	3.7	6.1	7.6	5.1	7	5.6	4.6	5.3	4.4	6.4	4	4.1	7.3	1	3	2.1	8.1	8.3	8.6	8.5	6.7	5.4	4.8	7.4	5.8	8.8	7.8	4.9	6.9	3.1	3.3	2.5	2.8

This model can be solved by transferring it to the linear programming (2) [41]:

$$\min \xi$$
$$s.t.$$
$$\left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi \ for \ all \ j$$
$$\left| \frac{w_j}{w_w} - a_{jw} \right| \leq \xi \ for \ all \ j$$
$$\sum_j w_j = 1$$
$$w_j \geq 0 \ , \ for \ all \ j$$

By solving this problem, the optimal weights $(w_1^*, w_2^*, \ldots, w_n^*)$ and the optimal value of ξ^* are obtained. ξ^* can be defined as the consistency ratio of the comparison system. It means that the closer ξ^* is to zero, the more consistent the comparison system is provided by the decision makers. The Equation (2) was used to check the consistency of the comparisons [56].

$$Consistency \ Ratio = \frac{\xi^*}{Consistency \ Index}. \tag{2}$$

The consistency index can be retrieved from Table 6. In this table, the lower the consistency ratio, the higher the reliability of the comparisons. As can be inferred from Table 2, in this case, "Blow out contingency", "Tight hole of the well and casing run problems", and "Pipe failure" are the most important drilling risks and "Disposal and discharge of wastewater and drilling fluid", "Lack of sufficient knowledge and information of field and reservoir structures", and "Changing social responsibility rules and regulations" are the least important drilling risks, respectively. As shown in Table 7, the comparisons show a high consistency as the value of consistency ratio of criteria is close to zero (the consistency ratio for criteria comparisons is 0.18).

Table 6. Consistency index.

a_{BW}	1	2	3	4	5	6	7	8	9
Consistency index	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Table 7. The risks' weights.

Criteria.	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24	R25	R26	R27	R28	R29	R30	R31	R32	R33	R34	R35
Weight	0.0327	0.0299	0.0312	0.0937	0.1773	0.0503	0.1595	0.0736	0.0404	0.0529	0.0382	0.1169	0.0332	0.0349	0.1608	0.0131	0.0271	0.0239	0.2023	0.2072	0.2179	0.2097	0.1268	0.0625	0.0438	0.1736	0.0873	0.2454	0.1863	0.0479	0.1469	0.0286	0.0290	0.0251	0.0261
Rank	26	28	27	14	7	19	10	16	22	18	23	13	25	24	9	35	31	34	5	4	2	3	12	17	21	8	15	1	6	20	11	30	29	33	32
ξ^*	0.98356948																																	
Consistency Ratio	0.18																																	

4.3. Prioritize Contract Alternatives Using the AHP Method

The purpose of this paper was to propose a model for selecting the most appropriate drilling contract based on risk analysis. Therefore, three models of the most common contracts of the onshore drilling industry were selected through expert opinions. Day-rate contract, Footage contract, and Turnkey contract options were described in detail in the literature review. As discussed earlier, they can be combined with incentive mechanisms, therefore there are six different contract alternatives. Given the impact of risk on project objectives (cost, time, quality, safety and environment), these calculations were performed by looking at overall impacts. In order to prioritize these contracts, the AHP method was used, which is explained below.

4.3.1. Development of the AHP Model

The design of the AHP hierarchy must satisfy the goal of developing a model that will allow operators or contractors to decide which drilling contract is more appropriate for their particular situation. The hierarchy developed in this study consists of three levels. The top level represents the goal of selecting the best onshore drilling contract. The last level is represented by the six alternative drilling contracts. The second level is the decision criteria that include 35 drilling risks in this article.

4.3.2. Determining the Comparison Matrix

Once the hierarchy was established, the pairwise comparison evaluation took place. The use of this AHP model requires the expert's judgment to discuss and determine the relative importance of each of the elements in the hierarchy. Each element in the third level (Drilling Contracts) was compared pair-wise with other elements at the same level, with respect to a criterion element. The pair-wise comparison was based on a scale of 1 to 9 as per the definition of weights given in Table 2. Table 8 shows a schematic matrix of pairwise comparisons of alternatives which was done for each criterion using Expert Choice software (V11.0, Expert Choice Inc., Arlington, USA).

Table 8. Pair-wise comparison matrix for six alternatives.

Pair-Wise Comparison Matrix for R1 Criterion	Day-Rate (X1)	Footage (X2)	Turnkey (X3)	Day-Rate Incentive (X4)	Footage Incentive (X5)	Turnkey Incentive (X6)
Day-rate (X1)	1	a	b	c	d	e
Footage (X2)	1/a	f	g	h	i	j
Turnkey (X3)	1/b	1/g	1	k	l	m
Day-rate Incentive (X4)	1/c	1/h	1/k	1	n	o
Footage Incentive (X5)	1/d	1/i	1/l	1/n	1	p
Turnkey Incentive (X6)	1/e	1/j	1/m	1/o	1/p	1

4.4. Relative Weight and Priority Evaluation

According to the results of pair-wise comparisons and data entry in Expert Choice software, the relative weight of each contract for each criterion against the cost target was calculated. The crossing product of all project evaluations using all criteria determined the final priority for each contract in relation to the desired goal. The mechanism for calculating the final priority was to sum the products of the multiplication of each criterion's priority weight by its alternative weight. The same process should be repeated for all six contracts. The final results for all contracts are shown in Table 9.

Table 9. Priority results for the drilling contracts according to the drilling risks.

Alternative Code.	Contract Type	Final Normalized Score
X1	Day-rate	0.65
X2	Footage	0.59
X3	Turnkey	0.71
X4	Day-rate Incentive	0.69
X5	Footage Incentive	0.86
X6	Turnkey Incentive	0.78

5. Discussion and Practical Implications

Construction contracts are one of the most crucial factors to address the challenging problem of risk management of a project. Hence project contract strategy and selection regarding the risks of a project can have a considerable impact on project success. Risks, which is defined as an uncertain event or condition that could occur, have an effect on project objectives [57], is an inevitable attribute of construction projects and actually the costs of them will be carried by the party who is determined to do so in the contract. The risks in construction projects can influence project key performance indices and basic objectives of time, cost, scope, and quality [58]. Project risk management has a significant impact on project performance because recognizing and handling the uncertainties majorly increases productivity in terms of cost, time, scope, quality, environment, and the other factors. Based on the proposed model in this research, impacts of risks on five different project objectives were assessed for selection of the most appropriate contract strategy. To this purpose, a WBM-based AHP system was developed in the context of the drilling projects. Firstly and based on a case, the recognized risks in the form of RBS were analyzed and the most effective (Blow out contingency (R1)) and the least effective (Changing social responsibility rules and regulations (R35)) ones were determined. These factors in the BWM were labeled as the best criterion and the worst criterion. However, based on a pair-wise comparison of available contract strategies as different alternatives, a "Footage Incentive" option was determined as the most appropriate contract strategy for drilling projects in Iran with the 8 dominant characteristics mentioned in Section 4.1. Reviewing the documents of the previous successful drilling projects in Iran, which have been implemented in the oil fields with the above mentioned features, shows that the results of the presented model, i.e., selection of the Incentive and Turnkey contract types, to an acceptable extent are consistent with the methods which are used in the industry. Since the presented RBS is a generic list of risks, the developed model can be adapted for contract selection of drilling projects in the oil or even gas fields with different characteristics. Therefore, the first party of drilling projects i.e., the client or her/his agent company can employ the presented systematic model to solve the project contract strategy selection problem. The main limitations of the current study were the lack of comprehensive references who address the risks of drilling projects and also the scientific approach for oil fields categorization and description of their contracts.

6. Conclusions

In this study, a novel approach has been introduced to solve the contract selection problem in the context of the drilling projects. The major contribution of this study can be divided into two parts: development of a generic list of prospective risks in a structured form named RBS. Also, proposing a risk-BWM Based model to solve the original problem of contract selection. Although the presented RBS has been developed for onshore drilling projects, it can be adapted for a wide range of underground drilling projects including offshore efforts and geothermal activities. The comprehensive RBS include four levels: one heading in level 0, eight main areas of risk in level 1, 34 sub-areas of risk in level 2, and finally 217 risk items in level 3. The above RBS have been formed in a bottom-up

method; firstly the 122 relevant risks in previous research were gathered and then they were purified and completed using the Delphi method. In the next step, the recognized risks were ranked considering their impact on project objectives and finally they were used to solve the contract selection problem through BWM. However, converting the risk items into decision criteria through assessment of their probable impact on project objectives can open up new horizons in decision making area in the early phases. Therefore, a decision making model was proposed for the determination of a contract strategy which itself is considered as one of the most significant parameters that affects a project's success. It is worth mentioning that it is crucial to select the most appropriate contract type in the pre-project planning phase, especially in drilling activities which are considered as high cost projects in the upstream sector of the petroleum industry.

Appendix A

Table A1. Risk breakdown structure of drilling projects.

RBS Level 0	RBS Level 1	RBS Level 2	RBS Level 3	References	RBS Code
Onshore Drilling Risk	Organizational/ Managerial Risk	Organization	Inadequate project organization Structure	[40]	1101
			Change of organization ownership or management	[59]	1102
			Improper project feasibility study	[40]	1103
			Lack of proper data bank for accidents/ keeping the accident data secret	[60]	1104
			Lack of sufficient resources to improve HSE	[60]	1105
		Project	Bureaucratic government system and long project approval procedure	[40]	1201
			Late internal approval process from the owner	[40]	1202
			Unclear and imprecise delegation of responsibilities and roles and project charter	[61]	1203
			Changes in the scope of the project	Survey	1204
			Failure to achieve the main target point	[62]	1205
			Lack of proper written work procedures and instructions	[60]	1206

Table A1. *Cont.*

RBS Level 0	RBS Level 1	RBS Level 2	RBS Level 3	References	RBS Code
		Planning	Weakness in planning and scheduling and initial project resources	[63]	1301
			Improper project planning and Budgeting and lack of accurate estimation of project value	[40]	1302
			Lack of emergency response plan	[60]	1303
		Design	Poor design	[64]	1401
			Design changes	[65]	1402
			Late changes to well design and procedures	[35]	1403
		Implementation	Inappropriate choice of project implementation method	[62]	1501
			Failure to predict the exact time to run the project	[62]	1502
			Failure to select the type of implementation or project contract according to the conditions	Survey	1503
		Project team	Incompetence of project team	[40]	1601
			Inefficiency or inexperience of the project team		1602
			Contractor's error	[66]	1603
			Making the wrong decisions	Survey	1604
			Inefficient and poor performance of Constructors	[40]	1605
			Excessive delays due to late decisions making by project participants	Survey	1606
		Management	Incompetence of project manager	[67]	1701
			Lack of meritocracy (in recruiting, organizing and promoting staff)	[60]	1702
			Incompetence of managers, supervisors and HSE crew	[60]	1703
			Lack of support from executives and senior management	Survey	174
		Human element	Lack of skills of drilling staff (inadequate practice of skills)	[68]	1801
			Lack of effective trainings	[32]	1802
			There is poor relationship between personnel and superiors	[32]	1803
			Inexperienced and less knowledgeable personnel	[59]	1804
			Unmotivated personnel	[3]	1805
			High stress and work pressure	[68]	1806
			The number of workers in workplace is not appropriate for the job (more or less)	[32]	1807

Table A1. *Cont.*

RBS Level 0	RBS Level 1	RBS Level 2	RBS Level 3	References	RBS Code
			The worker is injured or sick (temporarily, e.g., because of a flu)	[32]	1808
			Ergonomic problems due to fatigue and pressure of non-stop activities	[62]	1809
			Inadequacy of specialized personnel	Survey	1810
	Contractual Risk	Contract	Inappropriate contracts	Survey	2101
			Ambiguous conditions of contract	[40]	2102
			Improper verification of contract documents	[3]	2103
			Work conditions deferring from contract	[40]	2104
			Changes on scope of contract	[59]	2105
			Unballance share of legal risks between the parties	Survey	2106
			Contractual liability failure	Survey	2107
		Type and terms of contract	Unclear Contractual requirements	Survey	2201
			Changes in contract related rules and regulations	Survey	2202
	Economic Risk	Economic Changes and fluctuations	Changes in supply and demand	[63]	3101
			Changes in tax policy and tax rates	[63]	3102
			Oil price fluctuations	[65]	3103
			Exchange rate changes	[40]	3104
			Interest rate fluctuation	[40]	3105
			Inflation rate fluctuation	[40]	3106
			Instability of economic indicators of the host country	Survey	3107
			Increase of material cost	[40]	3108
			Increase of labor cost	[40]	3109
			Price instability of fuel and steel	[3]	3110
		Financial risk	Deficiency in Provide project funds	Survey	3201
			Increase the cost of materials and personnel	Survey	3202
			Improper cost calculations for the investment	[66]	3203
			Delayed disbursement of funds from financiers	[3]	3204
			Lack of economic production	Survey	3205
	Political / Social Risk	Government	Confiscation and nationalization	Survey	4101
			Expropriation	Survey	4102
			Change in contract provisions by the government	[63]	4103
			Reduction in annual budget allocation by government	[3]	4104
			Changes in foreign investment laws	Survey	4105

Table A1. *Cont.*

RBS Level 0	RBS Level 1	RBS Level 2	RBS Level 3	References	RBS Code
			Customs restrictions or the export and import of goods	Survey	4106
			Change in rules and regulations	[67]	4107
			Loss incurred due to corruption and bribery	[3]	4108
		The state of the host country	Rebellion	Survey	4201
			War/Vandalism	[64]	4202
			Terrorism	Survey	4203
			Political instability of the host country	Survey	4204
			Sanctions and special bans	Survey	4205
		Social Hazards	Sabotage measures	Survey	4301
			Lack of acceptance in local communities	Survey	4302
			Changing social responsibility rules and regulations	Survey	4303
			Negative attitude towards local oil and gas multinational companies	Survey	4304
			Changes in consumer demands	Survey	4305
			Workers' strikes	Survey	4306
			Dispute with residents around site	[40]	4307
	Geological Risk	Geological structure	Geological structure and complexity of the region	[65]	5101
			Geological Faults and Structures	[69]	5102
			Abnormal pressured zone	[64]	5103
			Unexpected natural subsurface obstacles	[62]	5104
			Man-made subsurface obstacles	[62]	5105
		Geological information	Lack of full knowledge of the field	Survey	5201
			Lack of sufficient knowledge and information of field and reservoir structures	Survey	5202
			Lack of accurate information on the structure and volume of the reservoir	Survey	5203
			Lack of accurate information on the fluid properties of the tank and how it is distributed in the tank	Survey	5204
		Formation	Different behavior of geological formations in different wells	Survey	5301
			Displacement of formations	Survey	5302
			Formation pressure	[35]	5303
			Total/partial losses in formation layers	[62]	5304
	Operational Risk	Well casing	Lack of well rehabilitation before casing running operations and the resulting problems	Survey	6101
			Problems with Reamer running into a well, such as Fishing or falling its rollers	Survey	6102

Table A1. *Cont.*

RBS Level 0	RBS Level 1	RBS Level 2	RBS Level 3	References	RBS Code
			Problem in Shoe and its installation and disruption in casing running	Survey	6103
			Float Shoe plaque while casing running	Survey	6104
			Damage to casing in the operational area, especially their threads due to incorrect transmission conditions	Survey	6105
			Changes in the size of the inner diameter of the casing in some parts due to impact	Survey	6106
			Lack of wrenches and tools suitable for casing running	Survey	6107
			Centralizers break during casing and liner running	Survey	6108
			Tight hole of the well and casing run problems	Survey	6109
			Problems with not installing Cager Hanger properly	Survey	6110
			Liner Lap leak and perform Seal Nipple Packer operation	Survey	6111
			Seal Nipple Packer leak if used	Survey	6112
			Casing corrosion and H2s migration to annulus	Survey	6113
			Casing Head Housing is not aligned for various reasons such as welding error and causing problems in the next phases of operation and installation BOPs	Survey	6114
		Pipelines	Pipe failure	[70]	6201
			Corrosion thinning	[70]	6202
			Defect of pipe	[70]	6203
			Interference from the third party	[70]	6204
			Incorrect operation	[70]	6205
			Corrosion fatigue	[70]	6206
			Unsuitable material	[70]	6207
			Blocking of the drilling pipe or product pipe installation due to the swelling of clay and silt	[66]	6208
			Sudden shock to the lines and the possibility of bursting pipes and fittings	Survey	6209
			Lack of a needle valve to relieve pressure	Survey	6210
			Faulty pipe connections: the improper fusion/welding of pipes	[62]	6211
			Inappropriate selection of external tube coating	[62]	6212
			Tight hole stuck pipe	[69]	6213

Table A1. *Cont.*

RBS Level 0	RBS Level 1	RBS Level 2	RBS Level 3	References	RBS Code
		Cementing	Cementing of long casing strings	[35]	6301
			Increase the well cavity and cementing problems	[62]	6302
			Problems in casing cementing and Staying cement in casing	Survey	6303
			Improper quality of cement slurry	Survey	6304
			Error in the amount of material added to the cement	[71]	6305
			Contamination of cement liquid with drilling mud or other caustic fluids	[71]	6306
			Error in choosing the type of cement class	[71]	6307
			Error in measuring the correct weight of cement	[71]	6308
			Cement Shrinkage	[71]	6309
			Insufficient drilling mud to replace cement inside the casing	[71]	6310
			Error in calculating the amount of cement required for the pipe	[71]	6311
			Non-compliance of cement program with operations and wells as a result of not performing the required tests correctly	Survey	6312
			Plugging the route of cementing during operation	Survey	6313
			Leakage of the route of cementing during operation	Survey	6314
		Loss of circulation	Formations that are inherently fractured, cavernous, or have high permeability	[69]	6401
			Highly fractured formations	[72]	6402
		Drilling Mud	Infiltration of mud into wells	Survey	6501
			Insufficient mud weight	[73]	6502
			Not testing the mud properties	[62]	6503
			Not testing water for the drilling fluid preparation	[62]	6504
			Drilling fluid seepage	[66]	6505
		Blow out contingency	Facing the high pressure layer in the drilling formation	[71]	6601
			Plug annulus	[71]	6602
			Annular Loss	[71]	6603
			Temperature effects on drilling fluid	[71]	6604
			Cut Mud	[71]	6605
			Error in density measuring equipment	[71]	6606
			Operator error in mixing the correct drilling fluid density	[71]	6607

Table A1. *Cont.*

RBS Level 0	RBS Level 1	RBS Level 2	RBS Level 3	References	RBS Code
			Improper casing running	[71]	6608
			Error inspecting Casing	[71]	6609
			Error inspecting Cementing	[71]	6610
		Wellbore instability	Collapsing formation	[74]	6701
			Mechanical failure by in-situ stresses	[69]	6702
			Erosion caused by fluid circulation	[69]	6703
			Chemical caused by interaction of borehole fluid with the formation	[69]	6704
			Wellbore shrinkage	[75]	6705
		Equipment	Corrosion or wear of mechanical parts	[60]	6801
			Effect of Ageing; wear and tear, worn or fatigued part	[35]	6802
			Equipment quality (special equipment; delay; damaged)	[35]	6803
			Inadequate equipment for more high-tech production	[63]	6804
			Inadequate equipment with type of operation	Survey	6805
			Poor maintenance program	[60]	6806
			Operational and resource limits	[35]	6807
			Material suitability and defects; Fabrication defects	[35]	6808
			Equipment Failure	[75]	6809
			Equipment failure due to H2S gas	[62]	6810
		Technology	New technology (e.g., packers and liner hangers)	[35]	6901
			Immaturity of new technology	[61]	6902
			Complex technologies	Survey	6903
			Lack of access to new technologies in geophysics and earth sciences	Survey	6904
			Risk of changes in upstream technology	Survey	6905
	HSE Risk—Health and Safety	Drilling operation	Start of drilling, Increasing pressure and cracking high-pressure lines of drilling fluid, colliding lines with people	Survey	7101
			Casing running, Falling suspended loads, work at heights, fatal falls, Stuck organs, collisions of pipes with people, collisions of elevators with the position of casing derrick man	Survey	7102
			Perforation, Falling suspended load, ergonomic damage, risk of employees falling from a height, hitting hammers on people, cracking of lines under pressure, explosion due to impact and electric current and lightning strike	Survey	7103

Table A1. *Cont.*

RBS Level 0	RBS Level 1	RBS Level 2	RBS Level 3	References	RBS Code
			Acidizing, Cracking of lines and hitting people, Acid spraying and severe acid burns, skeletal injuries	Survey	7104
			Cementing, Equipment damage, ergonomic discomfort, hearing problems, engine heat, heat stress, working with pressurized lines, tearing or cracking of lines, dust, falling and collision of equipment with people	Survey	7105
			Air drilling, Cracking of lines and hitting people, Abnormal and unusual noise	Survey	7106
			Underbalanced drilling, Hitting the plexus, ergonomic injuries, working at height and risk of falling from a height, hitting joints, shifting load, risk of falling load	Survey	7107
			Well Logging, Stuck of body parts, skeletal and muscular injuries, ergonomic injuries, noise, falling of equipment, collision of a tube stand with the position of the derrick man and damage to the position of the derrick man	Survey	7108
		Drilling equipment	Drilling rig installation, Stuck body parts between equipment, risk of falling load, falling from a height	Survey	7201
			Capsule storage, Sudden explosion of cylinders during displacement of toxic and combustible gas leaks, fire	Survey	7202
			Power supply device, Fire, stuck of organs inside machines and amputation, electrocution, burns caused by electric shock	Survey	7203
			Raise BOP, Work at height and risk of fatal fall, Risk of falling suspended loads	Survey	7204
			Coiled Tubing, Ergonomic injuries, collisions and damage to equipment and people, risk of falling, working with air lifts, working with pressure lines, cracking lines, spraying acid or diesel on people, skeletal and muscular injuries	Survey	7205
			BOP Test, Slipping, Infiltration of mud and fluids into people's eyes, falling into mud pit, Work at height, Failure to operate safety valves for drilling mud pumps, cracking of pressure lines, Elevators collide with people	Survey	7206

Table A1. *Cont.*

RBS Level 0	RBS Level 1	RBS Level 2	RBS Level 3	References	RBS Code
		Drilling operation	Groundwater contamination	[76]	8101
			Surface water contamination	[76]	8102
			Releases to air (local air quality)	[77]	8103
			Releases to air (contribution to global warming)	[77]	8104
			Visual impact	[76]	8105
			Biodiversity impacts	[76]	8106
			Land take	[76]	8107
			Noise	[76]	8108
			Traffic	[76]	8109
		Drilling fluid discharge	Soil pollution by drilling fluid	Survey	8201
			Groundwater pollution by drilling fluid	Survey	8202
			Adverse effects on wildlife	Survey	8203
HSE Risk—Environment		Disposal and discharge of wastewater	Soil pollution by wastewater	Survey	8301
			Visual impact in case of discharge to water resources	Survey	8302
			Water pollution by wastewater	Survey	8303
			Unpleasant odor emissions into the environment	Survey	8304
		Acid deposition	Soil pollution by acid	Survey	8401
			Air pollution caused by acid vapors	Survey	8402
			Unpleasant odor of acid	Survey	8403
			Groundwater pollution by acid	Survey	8404
		Oil and gas leaks, toxic gas leaks, waste or other environmental pollutants	Reduction of biodiversity of organisms due to biological accumulation of hydrocarbons	Survey	8501
			Damage to birds due to ingestion of petroleum products	Survey	8502
			Biological accumulation of petroleum substances in the body of organisms	Survey	8503
			Chronic effects for humans	Survey	8504
			Hypothermia and death of mammals/birds	Survey	8505
			Fire and damage to equipment	Survey	8506
			Explosion	Survey	8507
			Air pollution by gas	Survey	8508

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