Modelling the drilling crew induced process disruption factors using an ISM – MICMAC approach

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Abstract: Process disruption is a damaging situation in the petroleum sector as the industry involves heavy investments. In petroleum drilling operations, process disruption is inevitable mainly due to the many risks involved. The drilling crew related risk is one such potential cause of process disruption. In this paper, various drilling crew induced issues were identified through literature survey and expert discussion. The identified issues are categorised under respective crew induced process disruption factors. These disruption factors are analysed for their potential to disrupt the process, using interpretive structural modelling framework. Based on the driving and dependent potential of individual factors, they are clustered under autonomous, dependent, linkage and independent risk factors with the help of MICMAC approach. The analysis shows that psychological, physiological and cognitive risk factors have a high driving potential for process disruption, whereas leadership, technical prudence and interpersonal-relation factors have low driving potential and depend on other three factors to disrupt the process. The findings of the study could give valuable insights to rig managers, supervisors and decision makers in analysing their drilling crew and developing effective protocols and policies to enhance the crew climate and reducing crew induced process disruption.

Keywords: process disruption; drilling crew; interpretive structural modelling; ISM; leadership; MICMAC analysis; disruption potential; dependent potential; risk factors; risk management.

Reference to this paper should be made as follows: Rajagopal, G. and Ramasamy, R. (2020) 'Modelling the drilling crew induced process disruption factors using an ISM – MICMAC approach', *Int. J. Services and Operations Management*, Vol. 35, No. 1, pp.115–135.

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1 Introduction

India has both government-owned and private upstream petroleum companies that carry out drilling activities. However, owing to the risks involved, drilling operations are often outsource to third parties or performed as a joint venture. These risks may lead to huge loss of manpower, machine, milieu, material and money, if not managed appropriately (Crichton, 2005). Risks involved in drilling are event-related risks, as they are the outcome of operations in a situation of uncertainty (Aven and Renn, 2009). The uncertainty and unpredictability during the execution of process magnifies the complexity of risks (Aven et al., 2007). Exploratory drilling phase is highly susceptible to risks, some of the reasons being: varying geology, exploratory data availability, drilling mud interaction, crew related problems and logistic issues.

1.1 Problem statement

Human intervention is required at every phase of exploratory drilling; it is important to identify and analyse crew related attributes that hamper the successful completion of drilling process. Drilling crew includes the rig manager, who is the senior supervisor and ensures the smooth operation of rig. Drillers are responsible for the drilling operations and training the junior drilling crew members. Other categories of crew members like derrick-hand, motor-hand and rough-neck are responsible for equipment maintenance and providing crew assistance, while the lease-hand are responsible for general maintenance. The ability of the crew members to vigilantly identify and handle stressful situation and make appropriate remediation decisions in a timely manner could help minimise process disruption. It could improve performance and safety of both human and the process. Having a better understanding of the process and insight of possible issues, would facilitate crew members to easily tackle the risk as it arises (Alawamleh and Popplewell, 2011; Renn and Benighaus, 2016).

Most of the research studies related to risks in exploratory drilling is concentrated either on accident scenario analysis and process safety or operations related risks (Skogdalen et al., 2011, 2012). Very few studies have focused on impact of risks and uncertainties involved in drilling project that leads to completion time and cost over run (Sarkar and Yadav, 2013). Reader and Connor (2014) propose that human errors also contribute to triggering such risks. Though these studies have brought to light that drilling crew play a major role as disruption inducers, none have focused on how crew induced risks relate and interact with one another in bringing forth exploratory drilling process disruption. Hence, there is a need to study and understand the crew climate and related risks that impact the drilling process. The purpose of this paper is to identify the drilling crew induced process disruption risk factors and analyse them for understanding their individual and interactive disruption potential.

2 Research objectives

In order to solve the above problem, the following research objectives had to be achieved:

1 To understand how the drilling crew influences the various operations involved in the exploratory drilling process.

2 To identify various crew induced risks that potentially disrupt the drilling operations.

3 Categorise the identified risks under broader crew induced process disruption factors (CIPDFs) with the help of industrial experts.

4 Analyse each CIPDF with respect to its individual and dependent potential of driving the process disruption.

To realise the objectives, this paper is segmented into four parts. The first part explains the research methodology of identifying and categorising risks. The second part deals with the analysis of the categories using interpretive structural modelling (ISM) and MICMAC analysis. The third part involves the result and discussion. This section is followed by conclusions, which is the fourth part.

3 Research methodology

Crew resource is a major asset for any upstream petroleum sector involved in exploration and drilling. However, the same asset if not managed appropriately could cause process disruption and hamper the successful completion of drilling process. Process disruption leads to increased drilling completion time, cost, and wastage of resources. Hence, it is necessary to identify the crew induced factors that could disrupt the drilling process, analyse and asses them and remediate risks. Such an approach would not only ensure the process success but also strengthen the crew climate and its safety.

The identified CIPDFs were analysed for their potentiality of disrupting the process individually and through interaction with each other using the ISM methodology. The CIPDFs have been categorised further using Matrice d'Impacts croises – multipication applique' an classment technique (MICMAC) analysis also known as The cross-impact matrix multiplication applied to classification in English (Suprun et al., 2016).

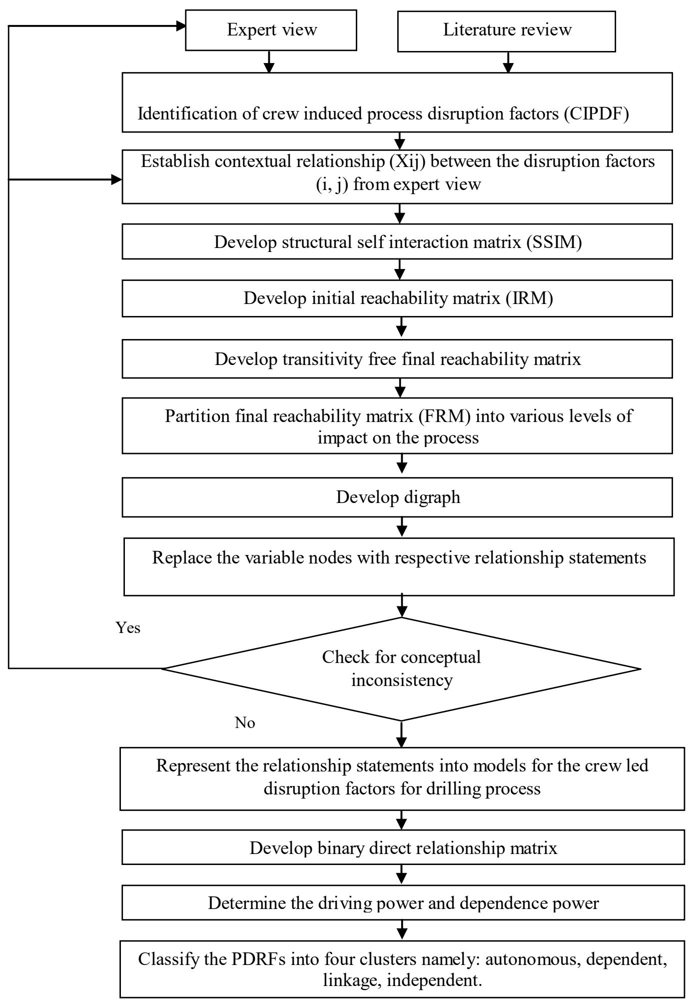
Methodology for developing the ISM framework is as explained below.

3.1 Interpretive structural modelling

ISM was first introduced by Warfield in 1973, after which this technique has found a wide spectrum of application in multifarious fields for decision making and analysis (Warfield, 1974a). Bolaños et al. (2005) have used this technique to clarify the perception of decision makers involved in a group decision making technique by enhancing knowledge sharing. Raut et al. (2017) have identified the critical success factor for implementing sustainable supply chain in oil and gas industry using ISM. Sarkar and Yadav (2013) have analysed factors leading to project risk and uncertainty.

ISM is a very effective model in terms of analysing the interaction of factors under study. It helps the researcher understand the effect of each individual factor on the subject/issue as well as in understanding how the factors interact with each other in causing the subject/issue (Diabat and Govindan, 2011). Its interactive approach helps decision makers to articulate even an ill-formed mental model into an understandable and well-defined model (Warfield, 1974a). The decision making is carried out either individually or through a group discussion where subject experts are brought together to discuss on the topic and arrive at a conclusion in consensus (Dewangan et al., 2015; Govindan et al., 2012). Computational complexity is a major drawback in ISM, but it could be overcome with the help of computer intervention. Another issue is its dependence on decision maker's expertise and experience; hence, Ajalli et al. (2016) emphasise on involving experts with more years of experience.

Figure 1 ISM – MICMAC methodology for analysing the crew characteristics



Source: Modified from Attri et al. (2013) and Raut et al. (2017)

In this study to analyse the CIPDFs, the following ISM model as shown in Figure 1 was developed and followed.

The developed ISM framework involves the following steps (Balaji and Arshinder, 2016; Diabat and Govindan, 2011):

Step 1 Issues leading to process disruption were identified through literature survey and interaction with experts. The issues were categorised under CIPDFs as shown in Table 2.

Step 2 These categories were represented in a self – structured interactive matrix (SSIM) as shown in Table 3.

Step 3 Initial reachability matrix (RM) was derived by converting SSIM matrix into a binary matrix as shown in Table 4.

Step 4 Final RM was developed by checking the initial RM for any existing transitivity as represented in Table 5.

Step 5 Level partitioning was carried out on final RM to partition the disruption factors according to their level of impact on the process.

Step 6 A directed graph was drawn based on the obtained relationship as shown in Figure 2.

Step 7 Finally, the developed ISM model was checked for conceptual consistency with the help of experts.

Step 8 Using the attributes' dependence and driving power derived from final RM, the MICMAC analysis was carried out. The attributes were classified under autonomous, independent, linkage and dependent categories.

3.2 Identification of CIPDFs

Various crew induced issues were identified from literature and through discussion with industrial experts. This study involved 7 industrial experts from a government owned Oil and Gas upstream company in Tamil Nadu, India. The demography of the experts has been represented in Table 1. The expert group comprised of senior members in the cadre of General Manager (GM), Deputy General Manager (DGM), Executive Engineer (EE), Senior Petroleum Engineer (Sr. P. Eng), Senior Drilling Engineer (Sr. D. Eng), and Instrumentation Engineer (Inst. Eng), with experience varying from 5 to 35 years in varied drilling domains as shown in Table 1.

Based on the literature and discussion with experts, 57 different factors were identified. These issues were reduced to 43 after eliminating the synonymous ones. With the help of experts, the issues were classified under 6 categories namely: Cognition risk, Interpersonal relationship risk, technical prudence risk, physiological risk, psychological risk and leadership risk. These risks are explained.

Table 1 Demography of industrial experts

Expert no.	*Age*	*Qualification*	*Years of experience*	*Designation*	*Domain expertise*
1	59	MTech	34	DGM	Drilling, HR
2	58	ME	35	GM	Drilling, maintenance
3	52	BE, MBA	29	DGM	Drilling, cementing
4	30	BTech	7	EE	Drilling, well planning
5	56	MTech	30	Sr. Pet. Eng	Drilling, testing, work over
6	38	ME	15	Sr. Drl. Eng	Drilling
7	33	BE	10	Inst. Eng	Drilling, Data logging

3.2.1 Cognition factor

The term Cognition is related to the capability of an individual to observe, understand and infer from a specific situation. Cognitive capacity differs from person to person. In a way this could be referred to the ability to draw inferences from data using common sense (Renn and Benighaus, 2016). In a drilling environment, it is very important to be aware of risks and anticipate them in any form and at any stage. Since the drilling crew is distributed across the field, higher level of situational awareness and better information sharing is required (Roberts et al., 2015). According to Sneddon et al. (2006) the workers' awareness of surrounding is very essential, but it is not adequate enough to ensure occupational safety. They suggest that awareness of the current process state is very important. Situational awareness and overall observation is very crucial in order to take proactive decisions and measures (Sneddon et al., 2013; Flin and Martin, 2001). It helps to perceive, comprehend and anticipate issues in a hazardous operation environment (Reader and Connor, 2014). For instance if a driller fails to recognise sudden increase of formation pressure compared to the hydrostatic pressure, it may lead to a kick that allows the formation fluid to enter the well bore (Burgerss et al., 1990). This would lead to a severe accident like blow out. Well blow out is a very dangerous situation that could lead to dismissal of further drilling (Xue et al., 2013).

Cognitive lag leads to flawed decision making and this occurs when the decision maker fails to recognise fine details that lead to unforeseen issues. Thorogood et al. (2000) emphasises on crew's commitment towards its outcome, as it would help them to structure and prioritise their tasks and plan implementation, and therefore improve their performance. Renn and Benighaus (2016) states that, while making a decision one must consider the effect of risk on the process. If the risk is perceived to be too meagre, then it could be averted. However, if it is identified to impact on the process and yet the outcome is profitable, then a decision to regulate the risk could be made. For example, drilling with alternate drilling mud when encountered with a thief zone (zone with high permeability) is an economical decision, as it is difficult to identify the extent of such zone and water based drilling fluid is far cheaper than synthetic or oil based drilling fluid (Rajagopal and Poosandaram, 2015). Crichton (2005) states that, while planning for a mitigation strategy, it is also important to consider the implications on the process, and Thorogood et al. (2000) adds to it by denoting that, ill thought remediation planning for an unexpected risk could harness futile or disastrous outcomes, and hence they emphasise the necessity to design remediation with an analysis of implication or outcome of implementation.

3.2.2 Interpersonal relationship factor

Interpersonal relationship is a very important factor to be considered when process execution is concerned (Thorogood et al., 2000; Sánchez and Al-Harthy, 2011). It is mainly needed to maintain crew – climate at its best. Since crew members are from varied cultural backgrounds, the interpersonal relationship and the crew climate could be affected (Amir-Heidari et al., 2015). When crew members fail to cooperate with each other, it may hamper the team's efficiency. Generally, interpersonal relations amidst team members get disturbed due to hierarchical differences in employment, where a team lead may not be so interactive with his junior crew members and at times show rude behaviour, or a senior driller may ignore the reports presented by a junior driller. When crew members are not good team players, the crew climate gets disturbed. Sometimes, a bad leader-crew relationship could also prevent appropriate information sharing amongst the crew members.

Due to bad relationship between the crew member and its lead, a crew member may hesitate to share any crucial information (Flin, 1995). Similarly, when crew members are not assertive and do not raise queries against the leaders decision even when it is not appropriate, both the crew and the facility could be at risk. Interpersonal relation is also hampered due to superiority issues, especially in a country like India where communal superiority issues are still prevalent, communal clashes between upper and lower community employees have caused potential process disruption. Similar problem also exists amidst members performing different activities like circulation, fluid designing, casing and cementing as they depend on each other's cooperation to coordinate their works (Mearns et al., 2001a).

3.2.3 Technical prudence factors

Technical knowledge and understanding is very important but situational application of knowledge is the essence. Technical prudence plays a major role in causing process disruption. Though crew members are experienced, they may not be in a position to perceive the depth of an issue or risk that could occur while drilling. Renn and Benighaus (2016) state that inability to extract or process probabilistic data may lead to wrong perception of risk in a situation and may lead to erratic decisions. Due to this lag in inferences, communication of risk also gets hampered. Violation of regulations, protocols or any logical rules is yet another issue. For example, when the bore hole is cemented with slurry that does not satisfy recommended standards, there are chances for loss of well integrity and therefore allows hydrocarbons to enter into the well. If data is not analysed or interpreted properly, this could lead to very dangerous situations like 'kick' (Reader and Connor, 2014).

Crew members must also develop knowledge about the equipment, their operation, handling and maintenance (Thorogood et al., 2000). For instance, when the drill string gets stuck up, releasing or retrieving the pipe is a tedious and time consuming process. Parts need to be fished out by experts, and in this situation, operational, equipment and handling knowledge are important. Inability to recover the stuck pipe may lead to temporary suspension of process and if the stuck up is severe, the well could also be abandoned.

3.2.4 Physiological factor

Health and safety is considered to be of at most importance when drilling crew is concerned. When a crew member falls ill, his level of performance would come down (Amir-Heidari et al., 2015). This may also interfere with his decision making ability. Stress and fatigue is yet another factor that causes physiological issues. Just like situational awareness, awareness of one's physique is also important to identify the extent of exertion that a crew member can handle. If work is performed beyond personal exertion limits, he/she could be subjected to stress which would limit the ability to take appropriate action as required (Crichton, 2005). Moreover, work environment and surrounding could also add up to this issue. Drilling crew working in the extreme cold regions like Alaska, find it difficult to work long hours (Ayele et al., 2013).

Similarly in Indian states like Rajasthan, Andhra Pradesh and Tamil Nadu where the climate is hotter, physical exhaustion is higher, hence, it would hamper the decision making capacity of the crew. Crew members with temporary disability due to any minor accidents may be unable to execute their duties, like handling heavy equipments, especially while performing trip-in and trip-out or casing operation. Prolonged strenuous work hours adds to this strain by causing muscular discomfort and blur the ability to think and make efficient decisions (Sneddon et al., 2013).

3.2.5 Psychological factors

Psychological risks relate to issues caused by crew member's state of mind at a specific situation. These are generally caused due to aggravated stress level. Psychology of a crew member inflicts upon his behaviour and attitude towards his fellow crew members. According to Mearns et al. (2004), prolonged work hours inflict on the psychology of the crew member, irrespective of his superiority in the crew. People who work long hours face stress related to work and less interaction with family and friends. Another issue is related to resistance to change, after prolonged exposure to a specific pattern of work or shift system, the crew members find it difficult to get accustomed to change.

Argumentative and harassing behaviour of crew members is another issue. It curtails one's interaction with fellow crew members as they make communication or extraction of any information difficult. One other issue that affects crew members' psychology is the concern about the installation safety and integrity especially regarding falling objects, personal injury or machine related injuries (Mearns et al., 2004). Regional and communal superiority is yet another influencing factor. It affects the crew member's attitude and triggers harassment towards their fellow workers (Kahan et al., 2011). Educational superiority also affects the crew climate by triggering discrimination towards lower level technical employees. Over confidence and sluggishness are two contradictory psychological issues that affect the member's participation in the crew activities in both extremes. Crew members with over confidence tend to dominate and those with sluggish attitude have limited participation in crew activities.

3.2.6 Leadership factors

Leadership risk relates to the incapability of leader in coordinating the team towards successful process completion within the stipulated time. According to Thorogood et al. (2000) leaders play a very challenging role as they need to be supportive team players, good decision makers and must have the ability to lead their crew safely and successfully even in stressful situations. When leaders fail to motivate their subordinate and junior crew members constantly, the team performance could be affected (Fröbel and Marchington, 2005; Flin, 1995).

Leader must recognise every crew member's effort and appreciate them instantly and openly. A leader also needs to identify crew member's capacity and capability, so that, appropriate work is distributed amongst the members and thus, ensuring a work environment with minimal stress and fatigue for the crew member (Crichton, 2005). Leaders also need to be easily approachable by the junior crew. Due to restrictions in approachability, acquiring and following up of important information at crucial times may be hampered. These issues generally curtail the leaders' ability to take safe and effective decisions (Thorogood et al., 2000). Similarly, when junior crew members are not included or their suggestions are disregarded during decision making, their real time field experience is overlooked and valuable information is neglected since junior drillers and engineers have direct exposure to the rig environment (Marchington and Kynighou, 2012).

Similarly, in a hazardous process like drilling, tacit knowledge is not sufficient for facing the uncertain situations, and hence timely and adequate communication is important. Maslen and Hayes (2015) have stated that timely communication of relevant information to appropriate group of people is challenging. However, overcoming such black swans could prevent hazardous disasters. The risk factors and their causes are shown in Table 2.

Table 2 Identified CIPDFs

Risk factors	*Causes*	*Reference*
Cognitive factors	Lack of understanding of the situation and overall observation	Flin and Martin (2001), Crichton (2005), Roberts et al. (2015) and Mearns et al. (2001b)
	Inability to identify issues/problems	Crichton (2005), Burges et al. (1990) and Mearns et al. (2001b)
	Flawed decision making under stress	Flin (1995) and Reader and Connor (2014)
	Failure to prioritise task	Crichton (2005), Roberts et al. (2015) and Sneddon et al. (2013)
	Failure of monitoring and problem spotting	Sneddon et al. (2006) and Roberts et al. (2015)
	Inadequate planning for implementation	Crichton (2005) and Thorogood et al. (2000)
	Ability to study/recognise the implication of plan execution	Crichton (2005) and Thorogood et al. (2000)
Interpersonal relation factors	Not being a team player	Thorogood et. al. (2000) and Flin (1995)
	Bad relationship with leader and crew	Flin (1995)

Table 2 Identified CIPDFs (continued)

Risk factors	*Causes*	*Reference*
Interpersonal relation factors	Lack of information sharing or partial communication	Reader and Connor (2014), Flin (1995) and Maslen and Hayes (2015)
	Not being assertive at risky situation	Flin (1995)
	No adherence to regulations	Mearns et al. (2001a)
	Crew members not following leader's command	
	Members do not respect each other's ethnicity community and belief	Alawamleh and Popplewell (2011) and Thorogood et. al. (2000)
Technical prudence factors	Inadequate technical skills	Thorogood et al. (2000) and Renn and Benighaus (2016)
	Lack of process understanding	Renn and Benighaus (2016)
	Inadequate system related knowledge	Renn and Benighaus (2016)
	Inadequate equipment handling knowledge	Renn and Benighaus (2016)
	Inability to understand and interpret critical data	Reader and Connor (2014)
Physiological factors	Personal limitations (exhausted easily or unable to work for prolonged time)	Crichton (2005)
	Physical disability	Amir-Heidari et al. (2015)
	Ability to handle equipments	Ayele et al. (2013)
	Health ailments	Amir-Heidari et al. (2015)
	Prolonged work hours	Sneddon et al. (2013)
	Reaction to existing environmental condition	Ayele et al. (2013)
Psychological factors	Attitude related issues	Reader and Connor (2014)
	Resistance to change	Mearns et al. (2004)
	Behavioural issues	Mearns et al. (2004)
	Argumentative behaviour	Crichton (2005)
	Depression due to monotonous work schedule	Ayele et al. (2013) and Thorogood et al. (2000)
	Limited interaction	Thorogood et al. (2000)
	Communal superiority/inferiority	Kahan et al. (2011)
	Over confidence/sluggish attitude	Redmill (2002)
Leadership factors	Not easily approachable	Redmill (2002)
	Does not Motivate the junior crew	Marchington (2005)
	Excludes junior crew members in decision making	Redmill (2002)
	Does not support team work	Thorogood et al. (2000) and Flin (1995)
	Lacks understanding of crew capability	Crichton (2005)

Table 2 Identified CIPDFs (continued)

Risk factors	*Causes*	*Reference*
Leadership factors	Inappropriate work load matching individual capacity	Crichton (2005) and Flin (1995)
	Does not Take ownership of safety and activity i.e., playing the blame game	Thorogood et al. (2000)
	Overlooks team disputes and coordination issues	Crichton (2005)
	Lack of appropriate information transfer/communication	Reader and Connor (2014) and Flin (1995)
	Does not Allow junior crew members to suggest	Crichton (2005) and Marchington and Kynighou (2012)

The issues identified and discussed here, were collected through extensive literature survey related to drilling process disruption and through discussion with petroleum drilling experts with more than 25 years of field experience. The broader risk categories or factors are comprehensive in nature as they capture the core of all identified issues that could affect drilling crew and lead to drilling process disruption.

3.3 Development of structural self - interaction matrix

SSIM indicates the relationship between risk factors *i* and *j*, in causing process disruption. While developing the SSIM for analysing the identified risk factors, specific relationship indicator need to be used. There are multiple relationship indicators as introduced by Warfield. Here, the interaction of the disruption factors among one another is studied and hence the relationship indicator 'leads to' has been used. There are four symbolic representations for indicating the interaction of the factors as shown in Table 3.

Table 3 Risk factor interactions

Symbols	*Interaction between risk factors* (*i, j*)
V	Category *i*, leads to category *j*, which disrupts the process
A	Category *j*, leads to category *i*, which disrupts the process
X	Category *i* and *j* both lead to each other causing process disruption
O	Category *i* and *j* are not related to one another

Table 4 Structural self – interaction matrix

Risk factors		*Leadership*	*Physiology*	*Psychology*	*Technical*	*Interpersonal*	*Cognitive*
1	Leadership	-	A	A	A	A	A
2	Physiology	-	-	V	V	V	A
3	Psychology	-	-	-	V	V	V
4	Technical	-	-	-	-	V	A
5	Interpersonal	-	-	-	-	-	A
6	Cognitive	-	-	-	-	-	-

The response for SSIM was collected in three phases. In the first phase, the problem topic and ISM methodology were explained to all the experts. In the second phase, questionnaire for analysing the impact of risks was developed and circulated to the experts and their responses were collected. The results were consolidated into single SSIM matrix through interaction with experts as shown in Table 4.

3.4 Reachability matrix

RM is a square binary matrix that is derived from the entries of SSIM. The transformation rules for converting Interaction symbols V, A, O and X into binary values is as shown in Table 5. Thus, the initial RM is obtained as shown in Table 6. Initial RM at times may have some transitivity, i.e., presence of indirect relationships.

Table 5 RM values for interaction symbols

(i, j) interaction symbol	*Reachability matrix entrants*	
	Entry at (i, j)	*Entry at (j, i)*
V	1	0
A	0	1
X	1	1
O	0	0

Table 6 Initial RM

Risk factors		*Leadership*	*Physiology*	*Psychology*	*Technical*	*Interpersonal*	*Cognitive*
1	Leadership	1	0	0	0	0	0
2	Physiology	1	1	1	1	1	0
3	Psychology	1	0	1	1	1	1
4	Technical	1	0	0	1	1	0
5	Interpersonal	1	0	0	0	1	0
6	Cognitive	1	1	0	1	1	1

It is important to identify the existence of transitive relationship between two factors by checking if factor A is related to B and if factor B is related to C. If they are related, then factor A is also related to C. For a matrix to be transitive it needs to satisfy the matrix property given in equation (1) (Warfield, 1974b). The final RM is shown in Table 7.

$$(M+I)^{n-1} \neq (M+I)^{n} = (M+I)^{(n+1)} = X \tag{1}$$

where

X matrix

M RM of – *X*

n a positive number less than the number of elements in the set.

Thus, the matrix representing all direct and indirect interactions, within the risk factors, are represented in the final RM.

Table 7 Final RM

Risk factors		*Leadership*	*Physiology*	*Psychology*	*Technical*	*Interpersonal*	*Cognitive*
1	Leadership	1	0	0	0	0	0
2	Physiology	1	1	1	1	1	1*
3	Psychology	1	1*	1	1	1	1
4	Technical	1	0	0	1	1	0
5	Interpersonal	1	0	0	0	1	0
6	Cognitive	1	1	1*	1	1	1

Note: *Represents the existence of transitive relationship between factor i and factor j

3.5 *Level partitioning*

The risk factors need to be partitioned with respect to their level of impact on the process, for which the reachability sets, antecedent sets and intersection sets need to be identified (Warfield, 1974a). Reachability set denotes the capability of a particular factor to drive another factor towards achieving the risk. Similarly, antecedent set depicts the dependence of the considered factor on other factors in causing the risk.

Table 8 Level Partitioning of drilling CIPDFs

R. no.	*Risk factors*	*Reachability set*	*Antecedent set*	*Intersection set*	*Level*
Iteration 1					
1	Leadership	1	1, 2, 3, 4, 5, 6	1	1
2	Physiology	1, 2, 3, 4, 5, 6	2, 3, 6	2, 3, 6	
3	Psychology	1, 2, 3, 4, 5, 6	2, 3, 6	2, 3, 6	
4	Technical	1, 4, 5	2, 3, 4, 6	4	
5	Interpersonal	1, 5	2, 3, 4, 5, 6	5	
6	Cognitive	1, 2, 3, 4, 5, 6	2, 3, 6	2, 3, 6	
Iteration 2					
2	Physiology	2, 3, 4, 5, 6	2, 3, 6	2, 3, 6	
3	Psychology	2, 3, 4, 5, 6	2, 3, 6	2, 3, 6	
4	Technical	4, 5	2, 3, 4, 6	4	
5	Interpersonal	5	2, 3, 4, 5, 6	5	2
6	Cognitive	2, 3, 4, 5, 6	2, 3, 6	2, 3, 6	
Iteration 3					
2	Physiology	2, 3, 4, 6	2, 3, 6	2, 3, 6	
3	Psychology	2, 3, 4, 6	2, 3, 6	2, 3, 6	
4	Technical	4	2, 3, 4, 6	4	3
6	Cognitive	2, 3, 4, 6	2, 3, 6	2, 3, 6	
Iteration 4					
2	Physiology	2, 3, 6	2, 3, 6	2, 3, 6	4
3	Psychology	2, 3, 6	2, 3, 6	2, 3, 6	4
6	Cognitive	2, 3, 6	2, 3, 6	2, 3, 6	4

Intersection or convergent set is composed of common elements or factors that are present in both the reachability set and antecedent set. Table 8 shows the level partitioning of drilling crew risk factors with iterations. Top level in ISM hierarchy is achieved by those factors that have same reachability and intersection set. Once such factors are identified and allocated a level, the factors are removed and the iteration is repeated. From Table 8, it could be observed that in the first iteration, reachability and intersection set for leadership risk factor have the same value; hence it is allocated level 1. The leadership factor is removed after level allocation. In second iteration, Interpersonal risk factor is observed to have same reachability and intersection set; hence it secures a level 2. Thus, in 4 iterations, the risk factors were level partitioned with respect to their reachability and intersection set.

A directed graph as shown in Figure 2 is generated to depict the hierarchy of influence of disruption factors based on the level partitioning as observed from Table 9. It exposes the interaction or causal relation amidst the CIPDFs that lead to disruption in petroleum drilling process.

From the digraph, the ISM model of CIPDFs is generated by eliminating the transitivity amidst the disruption factors and this is represented in Figure 3.

Figure 2 Digraph denoting the relationship amongst the CIPDF

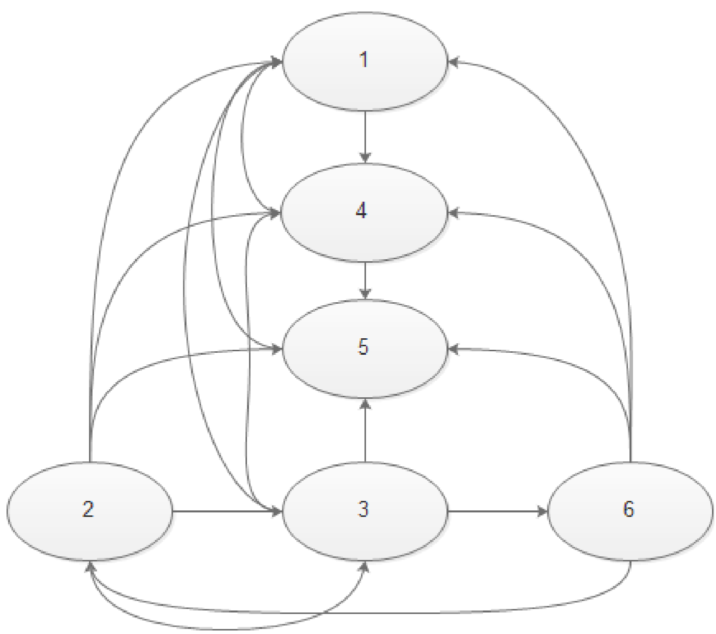
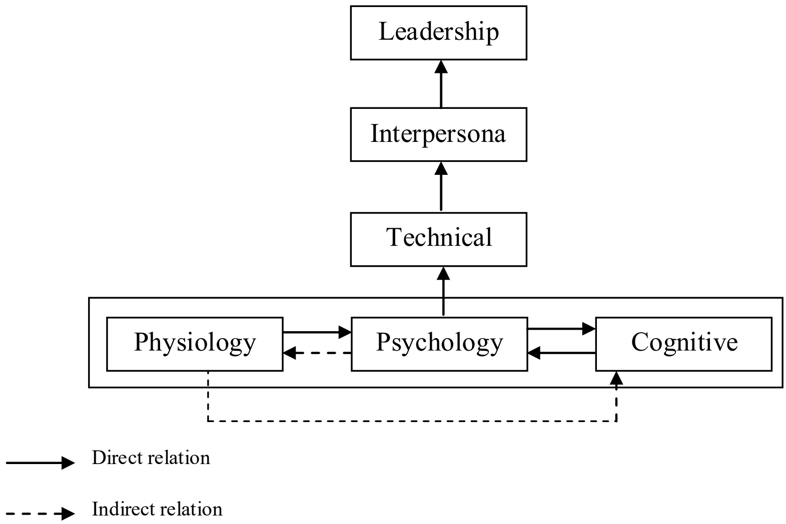


Figure 3 ISM model denoting the interaction between CIPDFs



3.6 MICMAC analysis

MICMAC analysis was first introduced by Duperrin and Godet (1973). This technique makes use of matrix multiplication properties (Diabat and Govindan, 2011). Here MICMAC analysis helps analyse the CIPDFs with respect to their driving power and dependence power derived from the final RM. The driver power is calculated by summing up all the row values denoting the interaction of a specific disruption factor with every other risk factor (Govindan et al., 2012). Dependence power is calculated by summing up all column values that denote how all risk factors interact with one particular risk factor as shown in Table 9. With respect to the driving and dependent power of risk factors, they are classified under four categories: autonomous, dependent, linkage and driving/independent risk category as shown in Figure 4. When an attribute falls under the Autonomous category, it indicates that it does not contribute to drilling process disruption at all and it is disconnected from the system due to its weak driving power and weak dependence power.

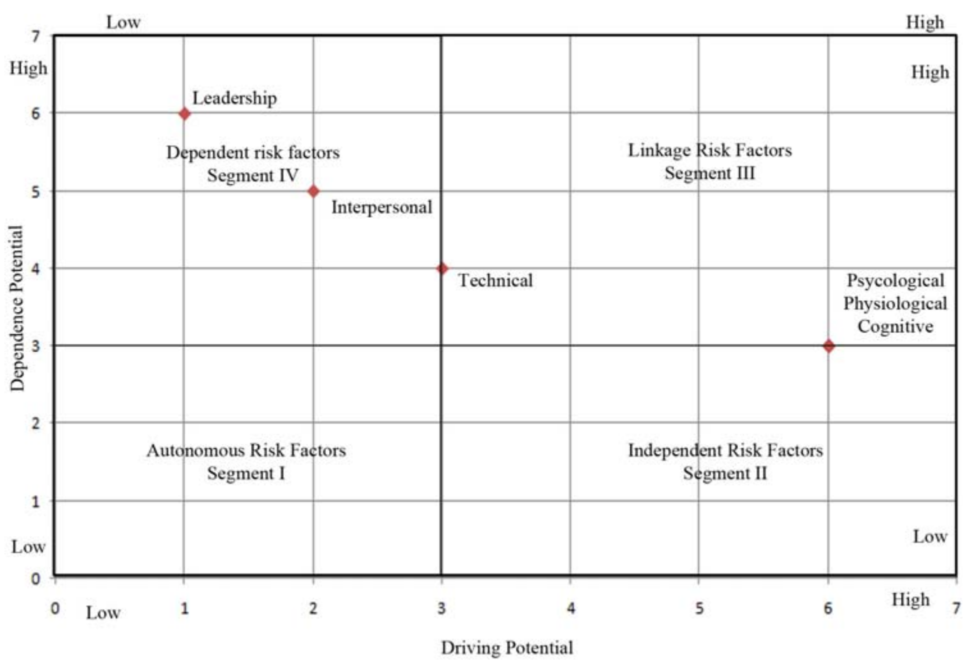
An attribute in the Dependent region indicates its weak driving power and strong dependence power. It denotes that this factor depends on other factors in causing disruption (Balaji and Arshinder, 2016). When a factor lies in Linkage region, it has strong driving and dependence power. These attributes are generally unstable hence any changes made in this regard will interfere with every other attribute. The fourth category or region is the Independent regions that exhibit weak dependence power but strong driving power and hence, it is also called as the key factor or in this case it could be the risk requiring higher focus (Raj et al., 2008).

Table 9 Dependence power and driving power of the CIPDFs

Risk factors		*Lead*	*Phy*	*Psy*	*Tech*	*IntP*	*Cog*	*Driving power*	*Ranks*
1	Leadership (Lead)	1	0	0	0	0	0	1	4
2	Physiology (Phy)	1	1	1	1	1	1*	6	1
3	Psychology (Psy)	1	1*	1	1	1	1	6	1
4	Technical (Tech)	1	0	0	1	1	0	3	2
5	Interpersonal (IntP)	1	0	0	0	1	0	2	3
6	Cognitive (Cog)	1	1	1*	1	1	1	6	1
Dependence power		6	3	3	4	5	3		
Ranks		1	4	4	3	2	4		

Note: *Represents the existence of transitive relationship between factor i and factor j

Figure 4 Driving power vs. depending power of CIPDFs – MICMAC analysis (see online version for colours)



4 Observations and discussions

The 6 CIPDFs that were identified from literature and expert discussions were analysed to understand their interrelation and interaction with one another. Thus, the ISM model was developed as shown in Figure 4. The model projects that the Leadership factor has the highest level of dependency and lowest level of ability to drive the process to disruption. It is easily influenced by every other disruption factor that is considered. This is followed by Interpersonal relationship risk, which is dependent on technical prudence, cognitive, psychological and physiological factors in causing disruption. Technical prudence factor falls in the third level, as this factor drives both interpersonal and Leadership risks and is dependent on the other three disruption factors. Similarly, Cognitive, Psychological and Physiological disruption factors are at the fourth level, indicating that they are very strong drivers that affect the other three categories in causing risk under study.

MICMAC analysis helps to rank and categorise the CIPDFs using its driving and dependence power as derived from Table 9. From the MICMAC diagram shown in Figure 3, it could be observed that none of the risk factors lie in the autonomous region. Thus, all the factors considered have the potential to disrupt the drilling process. Three of the disruption factors namely, Leadership, Interpersonal and Technical risk, are ranked 1, 2 and 3 in terms of dependence power and 4, 3, 2 in terms of driving power for disrupting the process respectively and fall in dependent risk segment. Similarly, cognitive, psychological, and physiological risk categories fall under the independent segment with a ranking of 1 in terms of driving power and 4 in terms of dependence power and these categories can disrupt the process individually.

The results denote that all the CIPDFs convey the potential to disrupt the drilling process. The ISM model stresses on the need of higher focus on cognitive, psychological and physiological factors of crew members due to their higher disruption driving power. This would also reduce the impact of factors that are highly dependent like the leadership factor, interpersonal relation, and technical prudence of crew members. Making the crew members aware of work safety and provide them appropriate training in non technical soft skills would certainly benefit in building strong crew values and ensure a better crew resource management.

Leadership factor has high dependency. It could be improved by emphasising the crew leader to be supportive and help manage a crisis in an efficient way. Crew leader could be trained to keep track and monitor each crew member's performance at various situations and keep up a mental and documented model on how each crew member has tackled conflicts and uncertain situations, along with daily performance. This would help to allocate capacity-appropriate work-load for crew members and also in streamlining training activities to enhance their ability. Leader could involve representatives of crew members at various levels during meetings; this would give a better opportunity in understanding ground-level issues and identifying new solutions with different perspectives. This would also help in bridging the communication barrier amidst the members. Hence, a crew lead must ensure an open and welcoming environment for the junior members. Additional training for the leader could be made mandatory to assess crew members' individual ability and ability to work in teams. Interpersonal relationship is another dependent factor that needs to be improved to ensure healthy crew work climate. Importance of good communication and relationship across levels need to be emphasised to members. Command following is necessary but members must be encouraged to be assertive and question any doubtful decision.

Members with different geographical background may have different approach of handling an issue and this variation must be embraced. Communal or educational superiority is one major issue faced by drillers, and members must keep in mind about the ultimate goal of 'process completion with minimal disruption' and overcome such issues.

Technical prudence is important, but its utilisation and timely application is entirely experience and cognition based. Training is a better approach to handle such issues. Timed training sessions could be designed to handle different situation using exercises embedded with adequate exposure to analysing and interpreting of data. This would help in improving situational perception and decision making. Physiological, psychological and cognitive risk factors are all entwined with one another in influencing the dependent risk categories that cause process disruption. Physiological issues could be overcome by providing routine medical attention combined with frequent counselling. Shift rotation could also provide relief from such exertion.

5 Conclusions

Through literature survey and discussion with industrial experts, 43 drilling crew induced issues were identified, and classified under 6 process disruption factors (CIPDFs). The CIPDFs were analysed for their individual and interactive potential to disrupt the drilling process using ISM–MICMAC analysis. The results of the analysis indicate that all the risks factors have the potential to disrupt the drilling process. Based on the responses of experts from the oil and gas company considered for the study, leadership factor has highest dependence power, whereas cognitive, psychological and physiological factors have highest driving power. These factors are independent factors and any change in these categories may hamper the crew situation which could potentially lead to disruption.

Based on the discussion with experts on the results obtained, it is suggested that for avoiding drilling process disruption, the organisation should focus on enhancing Cognitive, Physiological and Psychological aspects of the crew members, as it influences the leadership, technical prudence and interpersonal relationship risk factors. This can be achieved by infusing training, refresher courses, leadership programs, and constantly monitoring individual crew members for their behaviour and performance. The study also indicates an opportunity to develop and implement crew resource management, specifically designed to suit the crew members' capabilities and variability. In the future, the ISM model developed here will be validated using techniques like failure mode effect analysis (FMEA) and structural equation modelling (SEM). This study is a step towards reducing the impact of crew related issues on the drilling process, crew climate and safety. Crew lead, crew members and decision makers could use this analysis of CIPDFs in identifying and assessing the crew related factors that need to be focused to successfully execute drilling activity with minimal disruption risk.

6 Managerial implications

The uncertainty and risks involved in petroleum drilling processes increase the stress and work pressure among the crew members. As petroleum drilling process involves intensive human intervention, it is prone to risks caused by human errors which lead to process delay and disruption. The identified CIPDFs and their relative sub-sets can be used to develop a scenario based crew performance analysis tool. The crew members' individual and group performance at various scenarios can be recorded, scored and analysed for their potential to cause disruption risk. The recorded data would provide a platform to understand the individual capability of crew members. This would give an opportunity to managers to assign capability appropriate duties to crew members at various scenarios. Specialised drilling crew tailored training programs can be developed to enhance the skills of individual crew members with respect to their factor scores. Providing appropriate training would help maintain a healthy crew climate amidst the members even at time of stress. Thus, by focusing on the crew induced disruption factors, managers can reduce the 3Ds, i.e., delay, disruption and downtime that hamper the productivity and efficiency of operations of the drilling phase.

Acknowledgements

The authors wish to acknowledge Dr. Malliga Poosandaram, Professor, Department of Industrial Engineering, Anna University, for her constant guidance, support and contribution for this work.

References

Ajalli, M., Asgharizadeh, E., Jannatifar, H. and Abbasi, A. (2016) 'A fuzzy ISM approach for analyzing the implementation obstacles of electronic government in Iran', *Proceedings of International Conference on Science, Technology, Humanities and Business Management*, pp.29–30.

Alawamleh, M. and Popplewell, K. (2011) 'Interpretive structural modelling of risk sources in a virtual organisation', *International Journal of Production Research*, Vol. 49, No. 20, pp.6041–6063.

Amir-Heidari, P., Farahani, H. and Ebrahemzadih, M. (2015) 'Risk assessment of oil and gas well drilling activities in Iran, a case study: human factors', *International Journal of Occupational Safety and Ergonomics*, Vol. 21, No. 3, pp.276–283.

Attri, R., Dev, N. and Sharma, V. (2013) 'Interpretive structural modelling (ISM) approach: an overview', *Research Journal of Management Sciences*, Vol. 2, No. 2, pp.3–8.

Aven, T. and Renn, O. (2009) 'On risk defined as an event where the outcome is uncertain', *Journal of Risk Research*, Vol. 12, No. 1, pp.1–11.

Aven, T., Vinnem, J.E. and Wiencke, H.S. (2007) 'A decision framework for risk management, with application to the offshore oil and gas industry', *Reliability Engineering and System Safety*, Vol. 92, No. 4, pp.433–448.

Ayele, Y.Z., Barabadi, A. and Barabady, J. (2013) 'Drilling waste handling and management in the High North', in *2013 IEEE International Conference on Industrial Engineering and Engineering Management*, Bangkok, pp.673–678.

Balaji, M. and Arshinder, K. (2016) 'Modeling the causes of food wastage in Indian perishable food supply chain', *Resources*, *Conservation and Recycling*, Vol. 114, pp.153–167.

Bolaños, R., Fontela, E., Nenclares, A. and Pastor, P. (2005) 'Using interpretive structural modelling in strategic decision-making groups', *Management Decision*, Vol. 43, No. 6, pp.877–895.

Burgerss, T., Starkey, A.A. and White, D. (1990) 'Improvements for kick detection.pdf', *OilField Review*, pp.43–51, Schlumberger.

Crichton, M. (2005) 'Attitudes to teamwork, leadership, and stress in oil industry drilling teams', *Safety Science*, Vol. 43, No. 9, pp.679–696.

Dewangan, D.K., Agrawal, R. and Sharma, V. (2015) 'Enablers for competitiveness of Indian manufacturing sector: an ISM-fuzzy MICMAC analysis', *Procedia – Social and Behavioral Sciences*, Vol. 189, pp.416–432.

Diabat, A. and Govindan, K. (2011) 'An analysis of the drivers affecting the implementation of green supply chain management', *Resources, Conservation and Recycling*, Vol. 55, No. 6, pp.659–667.

Duperrin, J-C. and Godet, M. (1973) *Methode de hierarchisation des elements d'un systeme Essai de prospective du systeme de l'energie nucleaire dans son contexte societal*, Rapport Economique, Paris.

Flin, R. and Martin, L. (2001) 'Behavioral markers for crew resource management: a review of current practice', *The International Journal of Aviation Psychology*, Vol. 11, No. 1, pp.95–118.

Flin, R.H. (1995) 'Crew resource management for teams in the offshore oil industry', *Journal of European Industrial Training*, Vol. 19, No. 9, pp.23–27.

Fröbel, P. and Marchington, M. (2005) 'Teamworking structures and worker perceptions: a cross-national study in pharmaceuticals', *The International Journal of Human Resource Management*, Vol. 16, No. 2, pp.256–276.

Govindan, K., Palaniappan, M., Zhu, Q. and Kannan, D. (2012) 'Analysis of third party reverse logistics provider using interpretive structural modeling', *International Journal of Production Economics*, Vol. 140, No. 1, pp.204–211.

Kahan, D.M., Smith, H.J. and Braman, D. (2011) 'Cultural cognition of scientific consensus', *Journal of Risk Research*, Vol. 14, No. 2, pp.147–174.

Marchington, M. and Kynighou, A. (2012) 'The dynamics of employee involvement and participation during turbulent times', *The International Journal of Human Resource Management*, Vol. 23, No. 16, pp.3336–3354.

Maslen, S. and Hayes, J. (2015) 'Preventing black swans: incident reporting systems as collective knowledge management', *Journal of Risk Research*, Vol. 19, No. 10, pp.1246–1260.

Mearns, K., Flin, R. and O'Connor, P. (2001a) 'Sharing 'worlds of risk'; improving communication with crew resource management', *Journal of Risk Research*, Vol. 4, No. 4, pp.377–392.

Mearns, K., Flin, R., Gordon, R. and Fleming, M. (2001b) 'Human and organizational factors in offshore safety', *Work & Stress*, Vol. 15, No. 2, pp.144–160.

Mearns, K., Rundmo, T., Flin, R., Gordon, R. and Fleming, M. (2004) 'Evaluation of psychosocial and organizational factors in offshore safety: a comparative study', *Journal of Risk Research*, Vol. 7, No. 5, pp.545–561.

Raj, T., Shankar, R. and Suhaib, M. (2008) 'An ISM approach for modelling the enablers of flexible manufacturing system: the case for India', *International Journal of Production Research*, Vol. 46, No, 24, pp.6883–6912.

Rajagopal, G. and Poosandaram, M. (2015) 'Selection of base fluid for drilling mud using analytic hierarchy process', in *2015 IEEE International Conference on Industrial Engineering and Engineering Management* (*IEEM*), Singapore, pp.209–213.

Raut, R.D., Narkhede, B. and Gardas, B.B. (2017) 'To identify the critical success factors of sustainable supply chain management practices in the context of oil and gas industries: ISM approach', *Renewable and Sustainable Energy Reviews*, Vol. 68, pp.33–47.

Reader, T.W. and Connor, P.O. (2014) 'The Deepwater Horizon explosion: non-technical skills, safety culture, and system complexity', *Journal of Risk Research*, Vol. 17, No. 3, pp.405–424.

Redmill, F. (2002) 'Risk analysis – a subjective process', *Journal of Engineering Management*, Vol. 12, No. 2, pp.91–96.

Renn, O. and Benighaus, C. (2016) 'Perception of technological risk: insights from research and lessons for risk communication and management', *Journal of Risk Research*, Vol. 16, Nos. 3–4, pp.293–313.

Roberts, R., Flin, R. and Cleland, J. (2015) ''Everything was fine'*: an analysis of the drill crew's situation awareness on deepwater horizon', *Journal of Loss Prevention in the Process Industries*, Vol. 38, pp.87–100.

Sánchez, F. and Al-Harthy, M.H. (2011) 'Risk analysis: casing-while-drilling (CwD) and modeling approach', *Journal of Petroleum Science and Engineering*, Vol. 78, No. 1, pp.1–5.

Sarkar, D. and Yadav, S. (2013) 'Combined interpretive structural modelling and expected value method approach for managing project risks in oil exploration project', *International Journal of Decision Sciences*, *Risk and Management*, Vol. 5, No. 1, pp.35–54.

Skogdalen, J.E., Khorsandi, J. and Vinnem, J.E. (2012) 'Evacuation, escape, and rescue experiences from offshore accidents including the deepwater horizon', *Journal of Loss Prevention in the Process Industries*, Vol. 25, No. 1, pp.148–158, Elsevier Ltd.

Skogdalen, J.E., Utne, I.B. and Vinnem, J.E. (2011) 'Developing safety indicators for preventing offshore oil and gas deepwater drilling blowouts', *Safety Science*, Vol. 49, Nos. 8–9, pp.1187–1199.

Sneddon, A., Mearns, K. and Flin, R. (2006) 'Situation awareness and safety in offshore drill crews', *Congress of Technology and Work*, Vol. 8, No. 4, pp.255–267.

Sneddon, A., Mearns, K. and Flin, R. (2013) 'Stress, fatigue, situation awareness and safety in offshore drilling crews', *Safety Science*, Vol. 56, pp.80–88.

Suprun, E., Sahin, O., Stewart, R. and Panuwatwanich, K. (2016) 'Model of the Russian Federation construction innovation system: an integrated participatory systems approach', *Systems*, Vol. 4, No. 3, p.29.

Thorogood, J.L., Hovde, F. and Dag, L. (2000) 'Risk management in exploration drilling', in *SPE International Conference on Health*, *Safety, and the Environment in Oil and Gas Exploration and Production*, pp.1–9.

Warfield, J.N. (1974a) 'Developing interconnection matrices in structural modeling', *IEEE Transactions on Systems*, *Man and Cybernetics*, Vol. SMC-4, No. 1, pp.81–87.

Warfield, J.N. (1974b) 'Toward interpretation of complex structural models', *IEEE Transactions on Systems*, *Man and Cybernetics*, Vol. 4, No. 5, pp.405–417.

Xue, L., Fan, J., Rausand, M. and Zhang, L. (2013) 'A safety barrier-based accident model for offshore drilling blowouts', *Journal of Loss Prevention in the Process Industries*, Vol. 26, No. 1, pp.164–171.