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Why is the risk of industrial non-routine activities high and how can it be evaluated? An integrated approach

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ABSTRACT

Non-routine activities such as startup, shutdown, maintenance, and operation commissioning require increased human interaction with the corresponding process. Owing to operator or procedural violations, the risk of accidents can be high during non-routine activities, even though they are performed less frequently. To identify and evaluate the hazards of non-routine processes, an integrated method combining job hazard analysis (JHA), hazard and operability analysis (HAZOP), and deviation degrees is proposed. JHA is applied to break down an operational process into steps, which are further defined as nodes in HAZOP for hazard scenario analysis. The concept of deviation degree is defined by integrating the operational and control function deviations to quantify the deviation analysis. Finally, the heating-furnace startup process in an oil and gas gathering and transmission station was selected to illustrate the proposed integrated method. The results show that this method constitutes a systematical and intuitive approach to identify hazard scenarios and evaluate risks, as well as to establish preventive measures for non-routine processes.

1. Introduction

Process safety is an effective tool to help prevent major accidents and improve engineering practices, especially in chemical process industries [1]. Apart from facilities, equipment, and instruments, which are the primary objectives of process safety management, operational activities should also be included. However, conventional risk assessments focus mainly on mechanical components rather than operational processes [2]. In fact, a large number of accidents occur during the operational process because of human and organizational errors, and the complexity of operational procedures. Furthermore, a minor operational error can cause the failure of a process or an entire plant [3,4]. For example, the Piper Alpha Disaster in 1988 resulted in 167 deaths and approximately 3.4 billion dollars in financial loss. A critical pump with one redundancy had been turned off for repair, and the night crew that operated the platform was not informed of it owing to a failure of the permit-to-work system. Although causal factors such as defeated design and inadequate emergency were identified, the root cause seemed to be that *the permit pertaining to the maintenance and missing safety valve was not found* [5]. Assuming that proper communication was available between the shift teams, maintenance should have been completed and disaster would not have occurred. Therefore, more attention should be paid to risk assessment of operational activities.

Among all operational activities in process industries, two types can be defined: routine and non-routine activities [6]. Routine activities involve normal and daily operations, such as regulating valves, whereas non-routine activities refer to operations such as

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startup, shutdown, maintenance, and commissioning. Compared with routine activities, non-routine operations deal with complex site elements, including equipment, organization, management, personnel, and high uncertainty owing to dynamic changes in process conditions and human behavior [7,8]. Duguid studied incidents in the oil, chemical, and petrochemical industries, and pointed out that 53 % of incidents occurred in non-routine processes, despite the fact that non-routine operations took only 10 % of the operational time [9]. Bridges and Clark collected data on 47 major process facility safety accidents from 1987 to 2010 and classified them into different operation modes such as online maintenance, startup, normal operation, shutdown, and maintenance turnaround [10]. They found that 31 of these major accidents were related to non-routine activities, accounting for approximately 66 %. Hu pointed out that 78 % of accidents in the Chinese steel industry occur during non-routine processes [11]. Shin analyzed major industrial accidents from 2008 to 2012 and found that 58.7 % of the accidents occurred during the preparation and maintenance phases [12]. The aforementioned accident statistics show that the risk of non-routine activities, including startup, shutdown, and maintenance, is high and should be addressed specifically.

However, many chemical enterprises tend to pay more attention to normal activities and less attention to the risk of non-routine activities such as startups and shutdowns in their safety management systems [13–15]. Few theoretical studies have addressed the identification of hazards in non-routine processes [16]. At the plant site, operations during non-routine stages usually rely heavily on experienced operators and supervisors familiar with the procedures. A typical example is the BP Texas refinery explosion that occurred in 2005 during the startup of the ISOM raffinate splitter section. Although many causes, including technical and organizational, jointly led to the occurrence of the accident, important inducing factors were that the experienced night lead operator left early, and the supervisor left with no supervisor or technically trained personnel who replaced him [17]. Furthermore, non-routine activities are infrequently performed, leading to a lack of experience [18]. Therefore, experience-based operations for non-routine activities are inadequate. In addition, each person involved in non-routine activities should know the procedures and the risk of deviating from them. Therefore, systematic risk analysis and assessment are necessary to clarify procedures during non-routine activities and identify possible deviations from procedures.

The main contribution of this study is the proposal of a systematic risk analysis and assessment method for non-routine industrial activities. Given that there is currently no consistent definition of non-routine activities, this concept is clarified in Section 2. Subsequently, the difficulties of traditional methods are discussed, and an integrated risk assessment method is developed. In Section 3, the proposed method is applied to the heating furnace startup process of a gas gathering and transmission station as a case study. A discussion is presented in Section 4, and Section 5 provides concluding remarks.

2. Concept and method

2.1. Industrial non-routine activities

Given that many accidents occur during non-routine industrial activities, many studies have focused on safety management. However, to date, there has been no consensus on its definition. Researchers and experts have used different terminologies and classified patterns to specify them.

Ostrowski and Keim defined and enumerated two types of transient operations: non-routine or planned operations that occur infrequently, and abnormal or unplanned operations [19]. Casal and Olsen listed some abnormal modes of operation, such as shutdowns, restarts, and online maintenance, compared to the steady-state mode of operation [2]. Bridges and Marshall concluded that startup, shutdown, and online maintenance are non-routine (non-normal) modes of operation [20]. Jain et al. separated a process system into four modes: design, normal operations, simultaneous operations, and transient operations [21]. However, the classification boundaries for some activities were not clear. For example, process startup was categorized as both simultaneous and transient operations. Li et al. divided industrial operation processes into two categories: routine and non-routine operations [6]. They used gas transmission stations as examples to illustrate different operation modes and classified gas transmission startup and shutdown as well as venting and pigging processes as non-routine operations.

Although these previous studies presented similar descriptions, a definition of non-routine operations was not provided, and the boundaries of these descriptions were not clear. Terms such as transient, abnormal, non-routine, and non-normal operations are used imprecisely and interchangeably. In a recent study by Cutchen, the differences between routine, non-routine, and abnormal operations were explained, and their scope was delimited [22]. Three important characteristics of non-routine operations were presented: being planned, following established procedures, and being carried out infrequently. The main difference between non-routine and routine operations is the operating frequency (as Cutchen wrote, a routine operation is a normal day-to-day operation). Note that non-routine operations should be process-related operations, excluding temporary works by a third party. An example could be firework in process industries, which is a planned operation with established procedures carried out infrequently. However, this is a temporary operation that is irrelevant to the technological processes. In addition, non-routine activities are confronted with uncertainty regarding events, time pressure, managerial complexity, and technological complexity [23]. Hence, we define non-routine activities as follows.

- Non-routine activities are planned as normal activities with established procedures, rather than unplanned abnormal activities without established procedures.
- Non-routine activities are technological process-related activities.
- Non-routine activities are infrequent and have a relatively high degree of uncertainty, dynamism, and complexity.
- Based on the above definition, activities such as pre-startup, startup, shutdown, and commissioning are common examples of non-routine activities. For example, gas transmission shutdowns must be conducted if major maintenance or equipment replacement

programs are required. All shutdown activities are planned using established procedures. The process involves technological activities such as check valve, instrument, and equipment leakage. Gas transmission shutdown activities are rarely conducted at gas transmission stations. This process involves complex activities, and operators may lack experience. The duration of the process is typically limited owing to the requirement for continuous gas transmission. All these factors lead to uncertainty, dynamism, and complexity in shutdown activities. The characteristics of non-routine activities require particular attention when conducting process risk assessment.

2.2. Difficulties of traditional methods

Process risk analysis methods such as FTA, ETA, FMEA, bowtie, and HAZOP have proven to be effective in reducing the risk of accidents in the process industry [24,25]. However, fewer methods are available for the risk assessment of non-routine activities than for routine activities. One important reason may be that logical cause-consequence reasoning methods such as FTA, ETA, and FMEA are inadequate to describe the risk generation and evolution of non-routine activities, which rely heavily on manual operations and procedures. Commonly accepted hazard analysis and process management methods for non-routine activities include HAZOP, what-if analysis, safety audits, improved procedures, and extensive safety training [26]. Among these, HAZOP has been widely used to help identify hazards in both technological and operational processes.

The characteristics of HAZOP, which differ from those of other risk assessment methods, include the use of guide-words and the definition of process deviations [27]. By combining guide-words and analytical objects, possible hazard scenarios can be identified so that causal-factor and consequence analyses can be conducted. The U.S. Department of Energy Handbook provides the most common combinations of process parameters and guide-words [28].

To fully evaluate the hazards of a company, HAZOP should be conducted for all modes of operation. However, HAZOP has been applied mainly to piping and instrument diagrams (P&ID), while limited applications have been seen in operation procedures, especially non-routine processes [10,29]. Moreover, the standard HAZOP analysis of chemical processes is time-consuming and laborious, often taking weeks or months [30]. This is the same for HAZOP analysis of the operation procedure. Some scholars point out that HAZOPs of non-routine activities require more labor input because there are a large number of potential upset consequences for these activities [31]. One solution is to conduct computer-aided HAZOP, which has been proven to significantly reduce labor and save time in the standard HAZOP analysis of chemical processes [32–34]. However, few studies have focused on automating the HAZOP analysis of the operational process.

Another solution is to improve the HAZOP method by defining different guide-words. Specifically, a new group of guide-words was proposed to address deviations in the operation process. Ostrowski and Keim emphasized the importance of risk analysis for startups and shutdowns in industries, and developed a transient operation HAZOP (TOH) method for transient operations [19]. Four guide-words–who, when, what, and how long–were defined to describe the possible deviations in job tasks. For risk analysis in the plant commissioning process, Cagno et al. proposed a multilevel HAZOP in which each procedure is broken down vertically into steps, and each step is further broken down horizontally into operator, control system, and plant/process levels [23]. They defined different guide-words for each level by eliminating irrelevant words. For the operator and control-system levels, 'well done,' 'faster,' and 'slower' were possible guide-words while 'as well as,' 'misordered,' and 'repeated' were excluded. For the plant/process level, the same guide-words as those used in traditional HAZOP were adopted. Thus, the time spent by human resources to complete the HAZOP tables for each procedure was reduced from 20 h with standard HAZOP to 6–8 h with improved HAZOP. Bridges and Clark proposed two types of guide-words for non-routine modes of operation: 7-8-guide-word HAZOP, and 2-guide-word HAZOP [10]. Apparently, 2-guide-word HAZOP saves more time than 7-8-guide-word HAZOP.

Risk assessment studies for industrial non-routine processes are limited, and systematic methods are lacking. An integrated risk assessment method is presented in the following section.

2.3. Integrated risk assessment method

As stated in the definition of non-routine activities, normal activities are planned using established procedures. In other words, risk is generated by inadequate procedures (including no procedures) or procedures that are not followed. Therefore, the operation procedures must first be analyzed in detail. An effective method is to decompose the operation procedures into steps and consider each step as an analytical unit. Meanwhile, the time spent on a deep risk analysis of these steps should not be long because most non-routine activities require limited time. Another challenge in the risk assessment of non-routine activities is that probabilities are unavailable because non-routine activities are infrequently conducted.

Therefore, to conduct a systematic risk assessment for non-routine activities, the following three points should be addressed.

- How to guide to break down a non-routine process into steps
- How to save time while considering as many procedure deviations as possible
- How to characterize the risk value of procedure deviations

To address the first problem, the job hazard analysis (JHA) method is introduced. JHA is a risk analysis method designed specifically for job processes, including non-routine processes [18,35]. It has the advantages of simplicity and practicability, and has been one of the most widely used safety management methods in operation risk elimination and unfavorable event diminution in industry sites [36–41]. It usually takes several steps to complete a task, and the main function of JHA is to break down a job process into sequential steps based on operational procedures or experts' experience and knowledge [42]. Therefore, JHA can provide guidance for breaking down non-routine processes into steps.

Concerning the second problem, a simplified HAZOP is necessary for the reasons discussed above. As Bridges and Clark verified in their study, for less complex processes, the 2-guide-word HAZOP is efficient and time-saving, because it involves non-performed steps and steps performed incorrectly [10]. Therefore, two guide-words, namely 'no' and 'wrong,' were adopted in this study to help identify deviation and hazard scenarios for non-routine activities.

The third problem can be regarded as a problem of quantifying risk. Although a probability-based method can provide precise measurements of risk, extensive statistical data are required, and missing one influencing factor could cause a deviation in the results. In particular, complex elements are involved in the risk measurement of non-routine processes, most of which cannot be quantified. In addition, the variable and dynamic operating environment of non-routine processes makes statistical data unavailable. Therefore, probability calculations are unavailable for non-routine processes. An alternative method is to define a risk-rating principle by transforming a qualitative description into a quantitative value; for example, a risk matrix or risk priority number introduced in some previous JHA and HAZOP studies [43,44]. Risk is a product of probability and consequence. Several levels of probability are defined and displayed in a column, and several levels of consequence are defined and displayed in a row. Each intersection of a row and column represents a risk level [45]. In fact, the risk in an operation process can be seen as a deviation when a subject cannot finish its function [46]. From this perspective, the risk comes from the deviation resulting from the fact that the correct procedures are not followed, which attaches great importance to strict requirements for the operation process. Therefore, a novel risk quantification method is proposed from the perspective of function deviation.

We define two types of function deviation: operational function deviation and control function deviation. Correct operation is required for each step of a non-routine process; this is called operational function. Deviation may occur because of many factors, such as carelessness, inadequate training, excess workload, and poor communication. Thus, the function deviation is used to describe the degree of operation completion. However, the risk level of non-routine processes cannot be fully reflected by function deviations because appropriate control measures can reduce risk. Therefore, the control function, which refers to control measures, should also be considered. It is well known that the classical risk is defined as the multiplication of probability and consequence. From a deviation perspective, the operational function deviation describes the probability aspect of risk, whereas the control function deviation addresses the consequence. Furthermore, quantitative criteria are developed according to the extent to which the operational and control functions deviate from the expected state. Intuitively, the deviation degree is 1 if the task of the node fails completely and 0 if it is completed successfully. Similarly, the deviation degree of the control function is 1 if there are no control measures and 0 if the current control measures are equal to or exceed the expected ones. Five linguistic variables are defined for decision makers to judge the degree of deviation: complete deviation, major deviation, moderate deviation, minor deviation, and no deviation. Triangular fuzzy numbers (FTNs) are adopted to explicitly define the operational and control function deviation scales. For each scale, membership degrees between zero and one can be assigned according to the FTN [an integrated approach of the fuzzy risk assessment model and data envelopment analysis for route selection] (see Fig. 1). The five-level deviation assignment principle is presented in Table 1.

Both function and control function deviations can be quantified using the degree of deviation according to Table 1. The total deviation degree should be the weighted summation of the operational function deviation degree (OFDD) and control function deviation degree (CFDD) as follows:

$$\mathrm{TDD} = \frac{\alpha}{\alpha+\beta} \times \mathrm{OFDD} + \frac{\beta}{\alpha+\beta} \times \mathrm{CFDD} \tag{1}$$

where α is the weight of OFDD and β is the weight of CFDD. The weights are primarily determined by the implementation difficulty (e.g., estimated time and personnel resources) of the operation or control functions. For example, the weight of the CFDD is lower if the control function is implemented through education and training rather than through maintenance and transformation. Experts who are familiar with and participate in the operational process are expected to score α and β on the scale given in Table 2.

Note that the operational function deviation may involve both non-performed functions and functions performed incorrectly. For

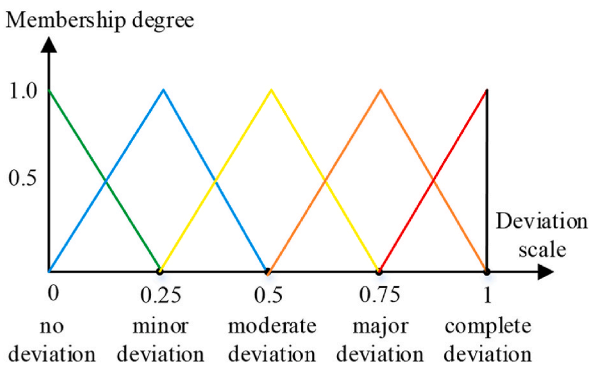

Fig. 1. Membership degrees of FTN.

Table 1
Five-level deviation degree assignment table.

Linguistic variables	Deviation degree scale
Complete deviation	(0.75, 1]
Major deviation	(0.5, 0.75, 1)
Moderate deviation	(0.25, 0.5, 0.75)
Minor deviation	(0, 0.25, 0.5)
No deviation	[0, 0.25)

simplicity, the OFDD can be calculated as the average of these two types of degrees, based on the assumption that the occurrence of a non-performed function or a function performed incorrectly is stochastic.

A flowchart of the integrated method is shown in Fig. 2. As described above, the JHA method can provide guidelines for node division and a definition for HAZOP analysis of non-routine processes. Furthermore, a 2-guide-word HAZOP method is employed for the deviation analysis of each operation node. To quantify the risk identified in each node, a method based on the deviation degree is proposed; this method considers both the operational and control function deviations.

Specifically, the method comprises the following steps.

(1) Choose a non-routine process as a case and collect information and material, such as procedures and process flowcharts. This process must be described in detail.
(2) Decompose the process into steps; each step has its expected function as a sub-goal of the process. Each step can be considered a node, and the functions are regarded as parameters of HAZOP.
(3) Analyze the possible deviations for each function using guide-words and further evaluate the deviation degrees.
(4) Analyze possible consequences and determine expected preventive measures. Evaluate the deviation degrees by comparing expected measures with current ones.
(5) Calculate the overall deviation degrees by averaging the operational and control function deviation degrees.

3. Case study

3.1. Non-routine process description

Heating furnaces are important devices widely used in oil and gas gathering and transmission stations. To reduce oil viscosity and avoid ice barriers, a typical method at these station is to increase the temperature of the oil and gas using heating furnaces. Apart from defects in the components, incorrect operation also accounts for most heating furnace failures. A complete risk assessment and analysis can help identify the hazards hidden in the operational process so that preventive measures can be implemented. In this study, the startup process of a water jacket heater was chosen to illustrate the practicability of the integrated method. In this startup process, operators follow the operating rules. The ignition operation can be performed before a series of preparations, including wearing PPE and checking instruments and valves. The decomposition of the heating furnace startup process is illustrated in Fig. 3.

At the workplace, the startup process of a heating furnace requires a strict sequence of operations. Any deviation from the standard operation procedures can cause failure of the startup task and even result in fires or explosions. A detailed risk assessment is presented in the following sections.

3.2. Risk assessment

According to the operational procedures, the nodes are defined based on JHA. Each step described in Fig. 3 is regarded as a node, and the corresponding tasks are the expected functions. For simplicity, two guide-words are considered: 'no' and 'wrong'. 'No' means that the functions were not performed at all; 'wrong' refers to inadequate functions. A group of experts familiar with both the JHA and HAZOP methods as well as with the water-jacket-heater startup process were interviewed to analyze possible deviations and assign deviation degrees. The risk assessment results for the heating furnace startup process are listed in Table 3. By comparing the expected functions with the most probable function deviations, a qualitative judgement can be obtained from experienced experts.

Taking node (2) as an example, the expected function is to check all connection points of the pipelines. With the guide-word of 'no,' the deviation can be defined as 'none of the connection points are checked,' which is a complete deviation scenario, and consequently the OFDD is 1. With the guide-word of 'wrong,' the deviation can be defined as 'some connection points of pipelines are not checked,' which is a major deviation scenario, and consequently the OFDD is 0.8. This is because the occurrence of a non-performed function and

Table 2
Intervals of α and β for reference.

Degree of implementation difficulty	Intervals of α and β	Operational function	Control function
Low difficulty	[0, 0.4]	Personal operation	Education and training, drill, etc.
Medium difficulty	(0.4, 0.6]	Communication	Monitoring, supervision, alarm, etc.
High difficulty	(0.6, 1]	Equipment state	Maintenance of equipment facilities, instruments, etc.

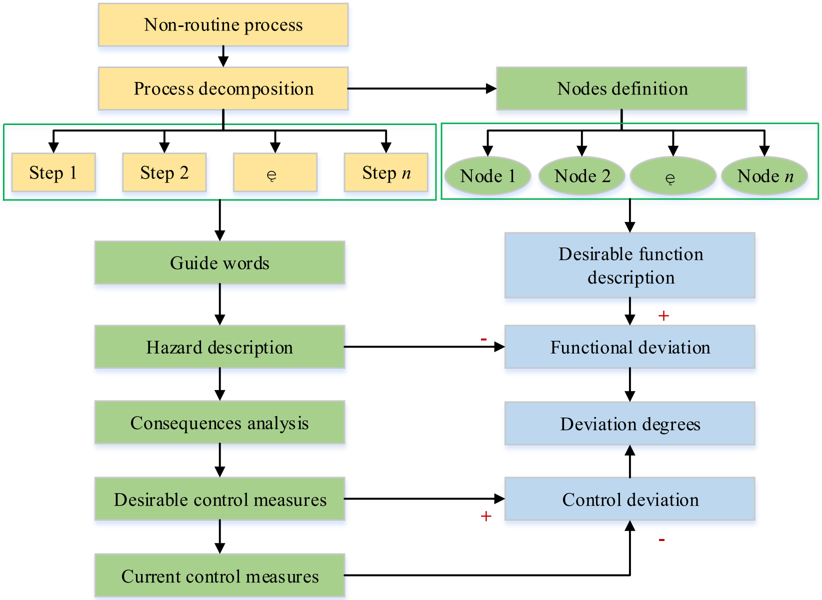

Fig. 2. Flowchart of the integrated method.

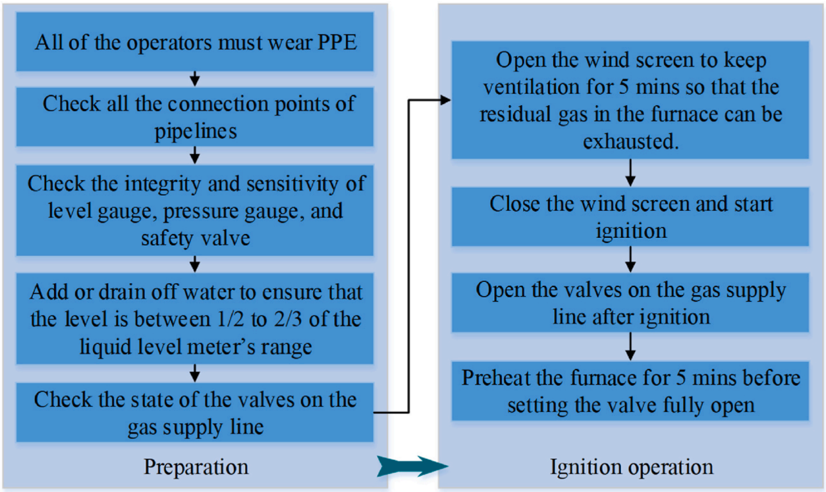

Fig. 3. Decomposition of a water-jacket-heater startup process.

a wrong performed function is stochastic. The ultimate OFDD is 0.9, resulting from averaging the OFDD of both deviation scenarios. To address the hazard scenario, implementing a lockout/tagout system and arranging specially authorized persons are expected control measures. However, current control measures only deal with supervisor assignments, and no lockout/tagout system is implemented. The control deviation level is moderate and the CFDD is 0.4. The implementation difficulty of the operation function on node (2) is low because it depends mainly on personal operation, whereas the implementation difficulty of the expected control function is moderate considering supervision-related control measures. Thus, experts assign 0.4 to α and 0.5 to β according to Table 2. Finally, the total deviation level of this node is determined by the weighted summation of OFDD and CFDD. The deviation-based risk assessment results for the water-jacket-heater startup process are presented in Table 3.

To intuitively represent the risk of each step during the water-jacket-heater startup process, a line graph of the function deviation degrees is shown in Fig. 4.

The grey line indicates the risk and difficulty of the operations on different nodes. Major operational deviations can occur on nodes (2), (3), (4), (5), (6), (8), and (9) without considering control measures. The blue line indicates the effectiveness of risk control measures. The orange line indicates that the total risk levels of nodes (2), (3), (4), (5), (8) and (9) are considerably reduced after considering the current control measures.

Table 3
Deviation-based risk assessment results for the water-jacket-heater startup process.

Nodes	Operational functions	Guide words	Deviation	Linguistic variables	OFDD		α	Expected Control function	Deviation (Current control)	Linguistic variables	CFDD	β	TDD
(1)	All of the operators must wear PPE	Wrong	Some operators do not wear PPE	Moderate deviation	0.4	0.4	0.3	PPE check for each operator	Current procedures do not include the checking phase	Moderate deviation	0.6	0.3	0.5
(2)	Check all the connection points of pipelines	No	None of the connection points are checked	Complete deviation	1	0.9	0.4	Perform the lockout/tagout system, and the authorized person should be different from the operators	Supervisors are assigned to the units but no lockout/tagout system is implemented in current units	Moderate deviation	0.4	0.5	0.62
		Wrong	Some connection points of pipelines are not checked	Major deviation	0.8								
(3)	Check the integrity of level gauge, pressure gauge, and safety valve	No	The indicator instrument and emergency valves are not checked	Complete deviation	1	0.9	0.5	Arrange and train professionals for indicator inspection	The operators are trained but no specialized personnel are assigned	Minor deviation	0.3	0.4	0.63
		Wrong	Checked but not repaired for integral functions	Major deviation	0.8								
(4)	Add or drain off water to ensure that the level is between 1/2 and 2/3 of the range of the liquid level meter	No	The liquid level is not checked	Complete deviation	1	0.85	0.5	Strengthen training and install automatic level controllers	The operators are well trained but there is no automatic level controller	Moderate deviation	0.4	0.7	0.59
		Wrong	The liquid level is too high or too low	Major deviation	0.7								
(5)	Check the state of the valves on the gas supply line	No	The valves on the gas supply line is not checked	Complete deviation	1	1	0.3	Strengthen training and assign an additional supervisor to monitor the operation	No additional supervisor is assigned but the operators are well trained	Minor deviation	0.2	0.3	0.6
(6)	Open the wind screen to keep ventilation for 5 min	No	No ventilation is performed	Complete deviation	1	0.85	0.6	The ventilation operation should be prescribed carefully in procedures and gas detection alarm should be installed	The procedures include the function but no gas detection alarm is installed	Major deviation	0.7	0.7	0.77
		Wrong	The time is less than 5 min and there is residual gas in the furnace	Major deviation	0.7								
(7)	Close the wind screen and start ignition	Wrong	The operator stands facing the furnace	Minor deviation	0.4	0.4	0.2	Put up no-standing signs on the front of the furnace	No-standing signs are deployed	No deviation	0	0.2	0.2
(8)	Open the valves on the gas supply line after ignition	Wrong	Open the valves before ignition	Major deviation	0.9	0.9	0.6	Strengthen training and install automatic interlock devices	The operators are well trained but no automatic interlock is installed	Moderate deviation	0.4	0.8	0.61
(9)	Preheat the furnace for 5 min before setting the valve fully open	No	The furnace is not preheated	Complete deviation	1	0.8	0.5	Strengthen training and assign an additional supervisor to monitor the operation	The operators are well trained and an additional supervisor is assigned	No deviation	0	0.5	0.4
		Wrong	The preheat time is less than 5 min	Major deviation	0.9								

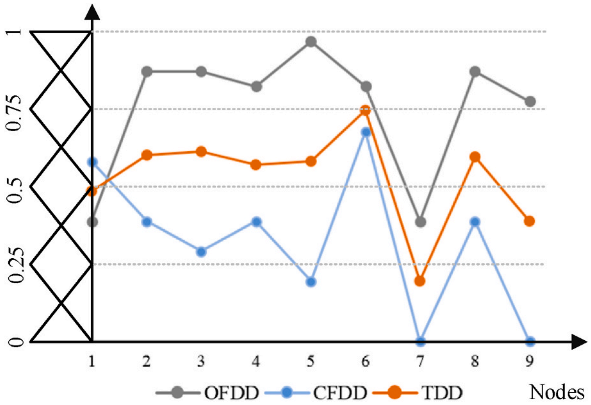

Fig. 4. Deviation degrees for each step of the water-jacket-heater startup process.

The line graph indicates that the deviation scenario (TDD = 0.77) on node (6) is the most dangerous and should receive more attention. Although the operational function deviation degrees of nodes (2) (OFDD = 0.9), (3) (OFDD = 0.9), and (5) (OFDD = 1) are higher than that of nodes (6) (OFDD = 0.85), adequate control measures can compensate for accident risk because the control function deviation degrees of nodes (2) (CFDD = 0.4), (3) (CFDD = 0.5), and (5) (CFDD = 0.2) are much lower than that of node (6) (CFDD = 0.7).

Accordingly, operational supervision for the water-jacket-heater startup process should focus on step (6), which is opening the wind screen to keep ventilation for 5 min, followed by steps (3) (checking the integrity of level gauge, pressure gauge, and safety valve), (2) (checking all the connection points of pipelines), (8) (opening the valves on the gas supply line after ignition), (5) (checking the state of the valves on the gas supply line), and (4) (add or drain off water to ensure that the level is between 1/2 and 2/3 of the range of the liquid level meter).

4. Results and discussions

Three key characteristics of non-routine activities were identified by redefining them as uncertainty, dynamism, and complexity. This reveals why the risk of non-routine industrial activities is high and requires an improved risk assessment method. The results of the deviation-based risk assessment of the water-jacket-heater startup process illustrate how the proposed integrated method addresses these issues. The JHA method is first used to guide the breakdown of a non-routine process into steps. The 2-guide-word HAZOP is adopted to identify deviations and hazard scenarios for non-routine activities. A fuzzy deviation quantification method is proposed to calculate the risk impact.

This study presents an integrated approach for risk assessment of non-routine activities by combining JHA, 2-guide-word HAZOP, and deviation degree. Previous studies presented process hazard analysis methods for non-routine modes of operation. For example, Cagno et al. proposed a multi-level HAZOP by breaking each procedure down into steps and breaking each step into operator, control system, and plant/process levels [23]. Different guide-words for each level were defined by eliminating irrelevant guide-words. They proved that the time spent by human resources to complete the HAZOP tables for each procedure was reduced from 20 h with the standard HAZOP to 6–8 h with the improved HAZOP. Ostrowski and Keim proposed a TOH approach using four main guide-words, including who, when, what, and how long, to describe the possible deviations of job tasks; each main guide-word was described through several explanations [19]. Twenty guide-words were required to serve as memory joggers and highlight the knowledge and experience of the evaluation team. Bridges and Marshall compared the what-if approach, 2-guide-word HAZOP, and 7-8-guide-word HAZOP for both continuous and batch processes, and concluded that the what-if approach takes much less time than the 2-guide-word HAZOP, and the 2-guide-word HAZOP takes much less time than the 7-8-guide-word HAZOP [20]. These three methods should be chosen for different procedures. The 7-8-guide-word HAZOP is applicable to those procedures with extreme hazards, the 2-guide-word HAZOP is suitable for less complex tasks or lower consequence scenarios, while the what-if method is applicable to low-hazard,

Table 4
Comparison of the proposed approach with existing ones.

Approach	Integrated approach (JHA, 2-guide-word HAZOP, and deviation degree)	Multi-level HAZOP	TOH approach	What-if approach	2-guide-word HAZOP	7-8-guide-word HAZOP
Generality	●●●	●●●●	●	●●●●●	●●	●●●●●●
Integration	●●●●●●	●●●●	●●●	●	●●	●●●●●
Simplicity	●●●●●	●●	●●●	●●●●	●●●●●●	●
Quantification	●●●●●●	●	●	●	●	●
Time saving	●●●●	●●●	●●	●●●●●●	●●●●●	●
Accuracy	●●●●●	●●●●	●●	●	●●●	●●●●●●

low-complexity, simple tasks.

To compare the proposed integrated approach with existing methods, such as multi-level HAZOP, TOH approach, what-if approach, 2-guide-word HAZOP, and 7-8-guide-word HAZOP, six characteristics were selected: generality, integration, simplicity, quantification, time saving, and accuracy. The number of dots indicates the extent to which an approach exhibits certain characteristics. Models with more dots have wider applicability than those with fewer dots. The comparison is presented in Table 4.

The success of non-routine activities requires strict operational procedures, and any deviation may cause job failure. This characteristic of non-routine activities requires a risk assessment to consider the potential deviation of each step. The proposed integrated risk assessment method provides guidelines for breaking down a non-routine process into detailed steps and further analyzing the deviation level for each step.

Compared with traditional risk quantitative methods, such as probability calculation and risk matrices, the proposed integrated method describes risk as the deviation of the actual operation situation from the normal one. Thus, the larger the deviation degree, the higher the risk. The deviation degree provides a more intuitive approach for process operators to understand possible hazards and control them, which helps in the awareness of risk for field staff. In addition, the probability value of an accident accurately indicates the risk level; however, it provides limited help for process operators and managers. In addition, small probability events can be ignored using probability methods. With the proposed method, small deviations from the normal operation procedure are analyzed to remind field operators and supervisors of the potential risk.

Another advantage of the integrated method is that it saves time, which is one of the most important factors affecting the risk assessment of non-routine processes. By adopting 2 guide-words, the time spent on risk assessment for one non-routine process was reduced from dozens of hours with the standard HAZOP to 2–4 h. In the meantime, the identified deviation scenarios are adequate because guide-words 'no' and 'wrong' can encode a detailed division.

5. Conclusions

Non-routine processes require strict operational procedures, and any deviation may cause failure of the entire process. However, there is a lack of systematic and practical methods for identifying and evaluating the risks of non-routine processes.

An integrated risk assessment for non-routine activities was developed to address three points: how to guide the breakdown of a non-routine process into steps, how to save time while considering as many procedural deviations as possible, and how to characterize the risk value of procedural deviation. The JHA method can systematically decompose a job process into steps that are defined as nodes in HAZOP. In the process of non-routine operations, deviations can be determined based on the difference between the actual and expected functions. In addition, the assessment time is usually limited to non-routine processes. Therefore, the guide-words for function deviation analysis are different from those used for technological parameter deviation analysis in traditional HAZOP. Hence, a 2-guide-word HAZOP was adopted to assist in the identification of deviation and hazard scenarios. Deviation degrees were used to measure the risk level; they are defined by integrating the operational and control function deviations. This integrated method can systematically identify hazard scenarios and evaluate the risk of a non-routine process. The heating-furnace startup process in oil and gas gathering and transmission stations was used as a case study to illustrate the proposed integrated method. By comparing the current control measures with the expected ones, preventive measures can be implemented. The risk assessment results can not only provide detailed guidelines for non-routine processes but also serve as a pre-job process safety checklist.

Data availability statement

The data associated with this study been deposited into a publicly available repository. Mendeley Data Reserved https://doi.org/10.17632/6nm6n8xrbg.1.

CRediT authorship contribution statement

Jiwang Zhang: Writing – original draft. **Weijun Li:** Writing – review & editing. **Yibo Sun:** Resources, Investigation. **Yin Liu:** Formal analysis, Data curation, Conceptualization. **Xiaolong Li:** Visualization, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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