Risk-based Performance Assessment from Fully Manual to Human-Robot Teaming in Pressurized Tank Inspection Operations

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Human reliability analysis, Risk assessment, Socio-technical System, Human-Robot Teaming

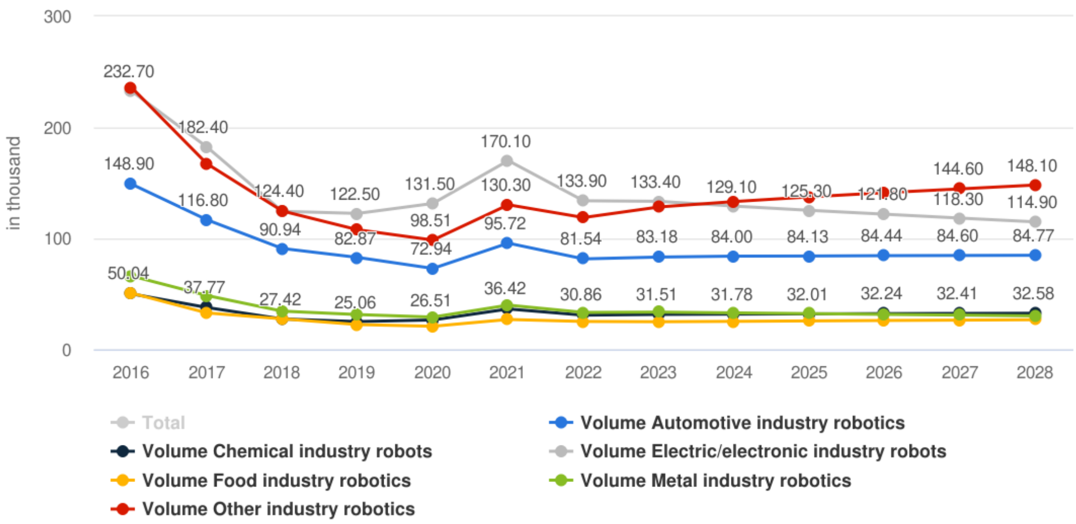
Abstract

The use of robotics in the process industry has shown a stable, increasing trend, according to survey reports, reducing the exposure of operators to critical operations, mainly during maintenance. Moving from full manual (FM) to human-robot teaming (HRT) operations is expected to reduce the risks for operators and increase operational efficiency. The methods used to assess system performances require an adaptation. Traditional risk assessment techniques are no longer adapted to analyze the new way of working; the previous methods proposed for HRT systems have been criticized for their fragmentation, complexity, and lack of validation.

This study proposed an integrated framework, including the qualitative and quantitative stages, to investigate the risk-based system performance and compare the full manual and human-robot teaming scenarios in pressurized tank inspection operations. The outputs demonstrated that the integrated framework worked for FM and HRT system performance assessment, considering multiple element types and their interdependencies, generating knowledge that can be exploited to reduce the system's risk and choose among different operational alternatives.

1 Introduction

The use of robotics as a primary characteristic of smart factories has become widespread in various industries(Martinetti et al., 2024;Caiazzo et al., 2023). According to Statista Market Insight, the total number of global industrial robots was 423.60 thousand in 2022 and was predicted to be 437.30 in 2028 (Statista Industry Insight, 2023). The changing trend details about primary industries are shown in Fig.1. The diffusion of industry robots is evidently more related to the broader mechanical domain while being less diffuse in the process industry. In any case, the direction of the phenomenon is stably raised. Around thirty thousand operating robots will be in the



process industry by 2028.

Figure 1 Total number of Industrial Robotics Worldwide for main industry applications (Statista Industry Insight, 2023)

As discussed by Borges *et al.* (2021) and Pereira *et al.* (2019), the introduction of robots in teams with humans is usually implemented to reduce the operators' workload while increasing productivity. On the other hand, the new actors in the work environment, when used in a team or in a collaborative way so that they are not separated from the human operators, have been recognized to cause psychological stress to humans (Gualtieri *et al.*, 2021).

Within the process industry, the benefits of introducing robots in operational teams can be maximized in heavy-duty operations, such as the positioning of piping or other equipment for monitoring, inspection, and maintenance in safety-critical environments(Murè et al., 2017). An example analyzed in this paper considers the periodic inspection of a pressure vessel system for early fault detection. In many countries, e.g., China, the pressure vessel equipment needs to be inspected periodically to verify the welding status. This activity is carried out by qualified technicians who have to work inside vessels in safety-critical conditions related to high temperatures, low-quality air, and high physical demand (Gerbec *et al.*, 2017). To improve working conditions and shorten inspection operations, the design of storage tank inspection robots has drawn significant attention in the process industry (Shukla & Karki, 2016; Mehak et al., 2024). As a typical human-centered activity, inspection and maintenance work in the process industry still needs human workers to be in the loop for flexibility (S. Li *et al.*, 2023). It is recognized that human error during maintenance activities increases the overall risk, directly resulting in potential major accidents and leading to long-term influence on system safety (Zarei *et al.*, 2021). Under the paradigm of Industry 5.0, technology design efforts should be dedicated to assisting rather than replacing human operators (Adriaensen *et al.*, 2023). Thus, human-robot teaming (HRT) would be a relevant operation scenario in modern process maintenance activities.

As discussed above, analyzing the risk of a system made of robots and humans and considering the specific factors affecting the safety of the different actors is a complex task(Colombo & Demichela, 2008). Sun *et al.* (2023) identified potential safety risks regarding physical, attentional costs, and psychological impacts in the construction industry. Their work provided a detailed understanding of how robots adversely affect workers' safety and health. However, it only considers the safety aspect of system performance and provides qualitative results. Borges *et al.* (2021) proposed an integrated framework based on a system dynamics model to predict the workstation performance after implementing the HRT system, focusing only on the ergonomic aspects. Reviews highlighted the main shortcomings that limit the practical applicability of novel risk assessment methods to HRT: fragmentation, complexity, and lack of validation (Huck *et al.*, 2021). In addition, the need to consider the factors that could affect the safety of operators and the efficiency of the operations in the long term was identified (Gualtieri *et al.*, 2021) as the need for integrating workers' personal aspects into the hazard analysis in the form of more human-centered specific guidelines to suit the HRT context better (Giallanza *et al.*, 2024).

Along with the concerns of the above-cited review, the need for risk assessment frameworks able to catch the complexity of the Human-Robot Interaction (HRI) system considering the specific technical and personal characteristics and their interdependencies arises, extending the requirements of ISO 10218-2 requiring industrial robot systems to undergo a risk assessment before commissioning (ISO, 2011) (Martinetti et al., 2021).

This paper intends to fulfill these needs, proposing a framework of methodologies and tools. introducing a novel task analysis structure, able to incorporate cognitive functions and dependencies among the subtasks. It allows the calculation of the overall risk considering the identified logical constraints through Integrated Dynamic Decision Analysis (IDDA). The framework is validated in the process industry domain, here applied to the HRT context, comparing risk-based system performance with manual operation scenarios.

This paper is organized as follows. Section 2 describes the integrated framework for risk-based system performance analysis. Then, as the validation of the proposed framework, the application in a case study and qualitative and quantitative results are provided in Section 3. After that, Section 4 will discuss the results and implications of the framework application. In the end, in Section 5, the conclusion is drawn with the discussions on limitations and future work.

2 The integrated framework

The structure of the proposed framework is shown in Fig.2. According to the traditional risk assessment procedure, the framework comprises a preliminary qualitative phase describing system tasks, interdependencies, and related hazards. A practical framework for a socio-technical system will better employ a top-down functional abstraction to detail the functions' characters at the system and single-element levels (Luther *et al.*, 2023). The qualitative part of the proposed framework consists of a top-down strategy from the system level to the element level.

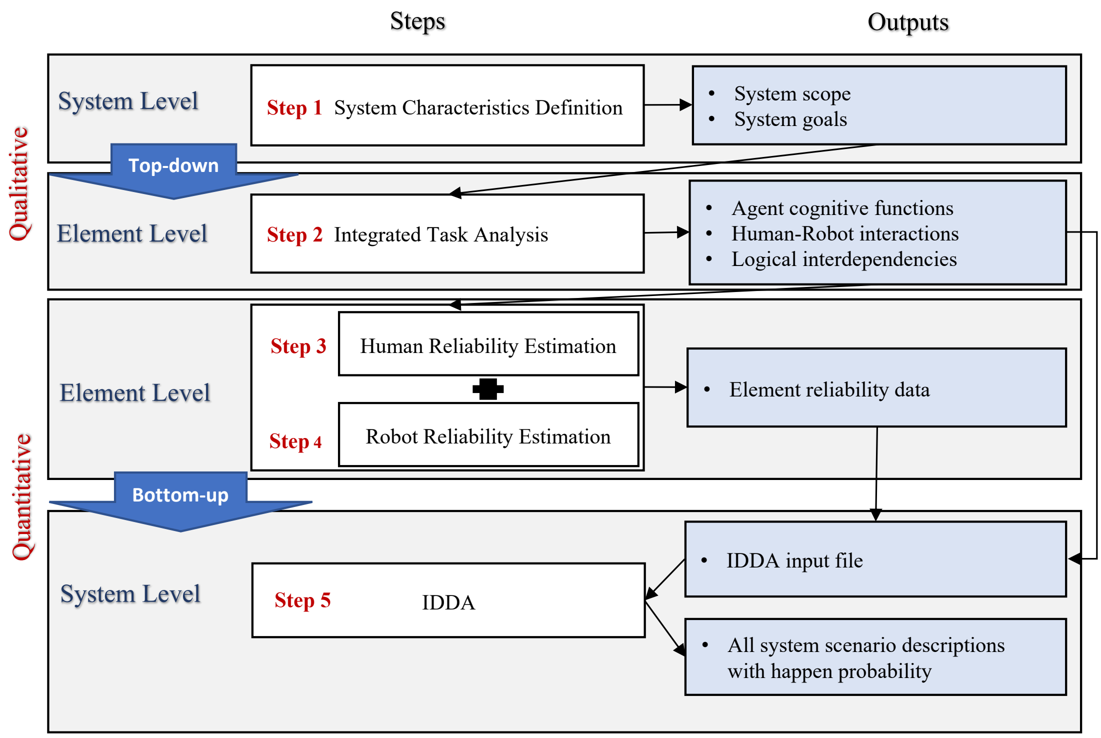


Figure 2 The integrated framework

Then, a quantitative phase is present to quantify the probability of unwanted outcomes and their consequences, thus obtaining an estimation of risk. The quantitative analysis phase consists of a bottom-up strategy from the element to the system level. At the element level, the second-generation HRA method CREAM is considered, extended with the Dempster–Shafer theory (DST) (Shafer, 1976; Dempster, 2008), and used to fuse the data from different experts to assess human reliability. Robot and equipment reliability data are derived from literature. At the system level, the Integrated Dynamic Decision Analysis (IDDA; Demichela & Piccinini, 2004) method integrates the components' reliability in a dynamic event tree, identifying and assessing the potential outcomes. That allows the probabilities and the consequences to be compared for the case in which the operations are performed by operators and the case in which robots in an HRT context support the operations.

2.1 Step1: system characteristics definition

The first step of socio-technical system analysis is identifying the system goals according to the stakeholders' expectations. The foundation of this framework is to clarify the boundary between the external environment and the target system and identify the system's goals. After that, the key interacting elements of the system should be specified, including the relevant organizations, humans, robots, equipment, and tools.

2.2 Step2: integrated task analysis

Task analysis is the study of what an operator or team of operators is required to do in terms of actions or cognitive processes to achieve a system goal (Kirwan & Ainsworth, 1992). In this research, task analysis is integrated with the cognitive functions each task demands. Four functions have been considered: Observation(O), Interpretation (I), Planning(P), and Execution(E) according to the correlation matrix with cognitive activities (Hollnagel, 1998) shown in Annex A (Table A.1). The CREAM methodology allowed to associate to each failure mode related to the cognitive activities a basic probability of occurrence (Table 1).

Table 1: The basic value for cognitive function failure modes(adapted from Hollnagel, 1998)

Cognitive function	Generic failure mode	Basic value
Observation	O1. Wrong object observed	1.0E-03
	O2. Wrong identification	7.0E-02
	O3. Observation not made	7.0E-02
Interpretation	I1. Faulty diagnosis	2.0E-01
	I2. Decision error	1.0E-02
	I3. Delayed Interpretation	1.0E-02
Planning	P1. Priority error	1.0E-02
	P2. Inadequate plan	1.0E-02
Execution	E1. Action of wrong type	3.0E-03
	E2. Action at wrong time	3.0E-03
	E3. Action on wrong object	5.0E-04

	E4. Action out of sequence	3.0E-03
	E5. Missed action	3.0E-02

This structure can be extended to represent the robot functions as the HRI model built based on communication theory (Frijns *et al.*, 2023). Task analysis also could recognize hazards and consequences. These characteristics are combined with the integrated task analysis in this study to reduce the procedure overlaps. An example of the main content of the integrated task analysis is shown in Table 2, which can also include location and tools columns if they have an impact on system performance.

Table 2 The integrated task analysis example

Task	Subtask		Actor	CFM	Hazard	Input	Output	Consequence
1 Set the robot	1.1	Connect the robot with a power strip	Operator	E3	Electricity shock		Robot with power	Occupational Accident
	1.2	Set the robot parameters	Operator	O1, I2, E3	Forget the right value		Robot got set	Time delay
	1.3	The get-ready indicating light turns on	Robot	E3		1.2	The signal sent by the robot	Time delay
	1.4	Observe the robot indicator	Operator	O1	Distraction	1.3	The signal received by the operator	Time delay
	1.5	Press the move start button	Operator	E3		1.4	Robot get stated	

- CFM: represents the cognitive function failure mode, as described in Table 1

2.3 Step3: human reliability estimation

CREAM, as a representative second-generation method, has been widely applied and validated in the energy and chemical industry (Hou et al., 2021; Jie Geng *et al.*, 2015), the maritime industry(Zhou *et al.*, 2017), and the transportation industry (Phillips & Sagberg, 2014). This method has integrated human cognitive, technological, and organizational factors to present a consistent error classification system (He *et al.*, 2021). CREAM allows the quantitation of human error probability following two steps. The initial error probabilities of the subtask could be obtained through Table 1, according to the cognitive function failure modes, which are the outputs of the integrated task analysis, e.g., the initial failure rate of missing an alarm, related to the missed observation will be associated to the generic failure mode O3 “Observation not made” with a probability of 7.0E-02. Then, the initial failure rate is corrected through a multiplier based on the level of Common Performance Conditions (CPCs), the assessment of which is performed through expert opinion aggregation. The list of CPCs and their assessment is shown in Table A.2.

One shortcoming of CREAM is that it does not provide any guidance for aggregating assessments across experts (Zheng *et al.*, 2020). To fill this gap, the Dempster–Shafer theory (DST) (Shafer, 1976; Dempster, 2008), also called a “theory of evidence," is employed to fuse the expert’s opinions on the CPCs. As a generalization of both probability and possibility theories (Ayyub & Klir, 2006), DST has the capacity to reduce uncertainty in evidence from different sources in an effective and valid manner (Kavya *et al.*, 2023). It is widely used in the process of combining evidence (Sezer et al., 2022; Bani-Mustafa *et al.*, 2020).

Consider a frame of discernment (FOD), $\Theta = \{H_1,\ H_2 \ldots H_n\}$, containing finite and mutual exclusive hypotheses on the status of a parameter. In this case, one FOD for each CPC was considered, and the set contained the possible levels that the CPC can undergo. Through its strength to a power set, all the possible combinations of the levels are represented and called propositions:

$$2^{\Theta} = \left\{\emptyset, \{H_1\}, \{H_2\}, \ldots \{H_n\}, \{H_1 \cup H_2\}, \ldots\ , \{H_1 \cup H_2 \cup \ldots H_i\}, \ldots \{H_1 \cup H_2 \cup \ldots H_n\}\right\}$$

Each expert can assign a value (weight) to each combination of levels between [0,1] based on belief in the proposition. This can be expressed as a basic probability assignment (BPA), also referred to as the mass function m: $2^{\Theta} \rightarrow [0,1]$, satisfying the Equation (1):

$$\begin{cases} \mathrm{m}(\emptyset) = 0 \\ \sum_{X \in 2^{\Theta}} m(X) = 1 \end{cases} \tag{1}$$

Where X denotes one of the propositions in 2^{Θ}. Suppose there are two mass functions, m_1 and m_2, from the same FOD. Fusing two BPAs collected from different sources could follow Dempster's combination rule, denoted by $m = m_1 \oplus m_2$, which is defined by Equation (2) and (3):

$$m(X) = \begin{cases} \frac{\sum_{B \cap C = X} m_1(B) m_2(C)}{1-k}, X \neq \emptyset \\ 0, X = \emptyset \end{cases} \tag{2}$$

$$k = \sum_{B \cap C = \emptyset} m_1(B) m_2(C) \tag{3}$$

Based on the combined weights collected from the experts, the level of each CPC could be selected, and the corresponding multiplier for each cognitive function could be assigned according to Table A.2. After that, the adjusted value for basic cognitive function failure modes will be calculated.

2.4 Step 4: robot reliability estimation

The essential components of an inspection robot include a mechanical part, control system, sensor, and actuator. The mechanical part with a moving crawler will help the robot move easily on the surface. Manipulation parts, the end-effectors, are relatively important as they perform polishing or magnetizing jobs. The actuators provide power to other parts with the functions of servomotors, drivers, and transmission systems. Sensors like the camera and radar sensor can obtain data from the mechanical system and information about the environment (Siciliano *et al*., 2009). The control system comprises a processor, software, and controller. According to China's regulation regarding industry robots, the MTBF (mean time to failure) should be no less than 50,000 hours, corresponding to a failure rate 2.0E-06.

From the literature (Carlson *et al*., 2004) it was identified the distribution of failure rate of the different parts: 32% of the failures descend from the control system; 27% pertain to the effectors; 16% relate to the communication; 12% depends on sensing failure and another 12% to the power failure. Adopting the cognitive function approach also for the robot, it can be stated that the sensing failure and the power failure contribute to observation function failure, the control system and the power failure contribute to the interpretation function failure, the control system and the power failure contribute to the plan function failure, and the effector failure, power failure and communication failure contribute to the execution failure. Thus, by combining the legal requirements for robot failure rates with the part contribution, it is possible to assess a required threshold failure rate for robot parts (e.g., the failure of the sensor, contributing 32% of the cases, will bring to a threshold failure rate of 6.4E-07). Then, the failure rates of the parts are combined to obtain a failure rate for the different functions of the robot, as shown in Table 3. These threshold failure rates will be used in the probabilistic assessment unless more precise data should be available. The dependencies will then be considered in the logical probabilistic analysis carried out through IDDA.

Table 3 The failure rate for robot function

Robot Function	Threshold Failure Rate
Observation (Power + Sensing)	4.8E-07
Interpretation (Power + Control system)	8.8E-07
Plan (Power + Control system)	8.8E-07
Execution (Power + Effectors + Communication)	1.1E-06
Communication	3.2E-07

2.5 Step 5: Integrated Dynamic Decision Analysis (IDDA)

Once the probability has been determined for each single element in the system, they are integrated into a wide picture through IDDA. The IDDA method is based on an enhanced form of event tree (Demichela & Piccinini, 2004), based on a logical-probabilistic modeling of a system integrated with its phenomenological model (Clementel & Galvagni, 1984; Demichela & Camuncoli, 2014). This method can consider event interdependencies in the form of logical constraints that can alter the tree's structure, force its outcomes at different levels, or update run time events' probability of occurrence. It has been validated in many process risk assessment cases (Baldissone *et al*., 2016; Demichela & Camuncoli, 2014; Gerbec *et al*., 2017). Based on the outputs from integrated task analysis (step 2), human reliability estimation (step 3), and robot reliability estimation (step 4), an input file of a set of mutually self-excluding sequences with occurrence probabilities is developed. A simple example of the IDDA modelling approach to specifying a risk model is presented in Fig.3. The IDDA method can fully represent the system state according to all the possible propagating paths generated from an input file developed on a specific system, and will constitute the tool to assess the system performances.

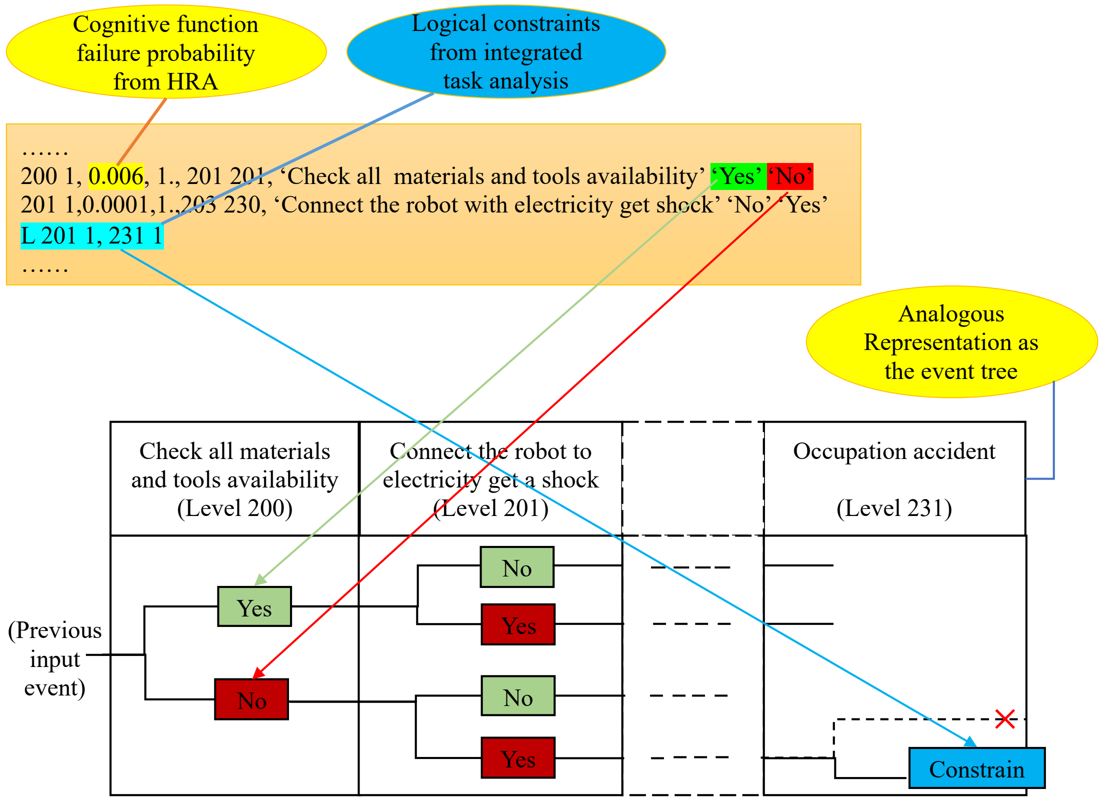


Figure 3 Example of the input file to the IDDA software tool and its analogous event tree structure

3 Applications in pressurized tank inspection

3.1 Case description

The case study used to verify the proposed approach was a rare inspection operation performed periodically (every ten years), including both Fully Manual (FM) and HRT scenarios. The case was provided by the Special Equipment Inspection Institute in Zhejiang, China, which supported the research from the data collection and expert opinion through:

(1) Semi-structured interviews with technicians. They all have 7~10 years of practical experience in pressure vessel inspection projects.

(2) Technical document collection. Relevant inspection documents were collected to provide operation details, including the inspection organization plan, scheme, technical standards and guidelines, risk and hazard list, and emergency response plan.

(3) Field investigation. A team of three scholars performed a field investigation of a pressurized spherical tank inspection process, both in the full manual and human-robot scenarios were visited and recorded (Fig.4)

(4) experts' opinion collection for the CPCs of CREAM setting, five experts in chemical or human factors have more than five years of experience were invited to give the weight of the CPCs levels 3.4 gives the details of the CPCs' setting process.

Figure 4 The FM and HRT inspection scenarios

The specific pressure vessel is a 5000 m^3 spherical, above-ground LPG storage tank. The FM scenarios require the examination of the weld joints from inside the spherical tank performed by four different teams:

1) The plant team (Team 1) is responsible for preparation and environment setting.

2) The construction team (Team 2) is responsible for the scaffold-related work.

3) The polishing team (Team 3) is responsible for welding joint polishing work.

4) and testing technician team (Team 4). responsible for welding joint magnetic and crack identification work.

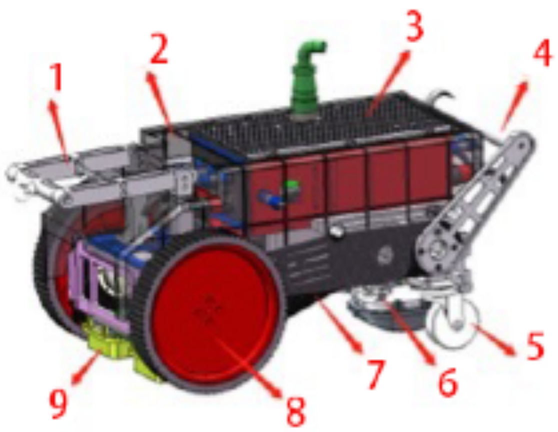
Teams 2, 3, and 4 are made of two groups, which will hand off every 2 hours.

The HRT scenarios require two teams:

1) The plant team (Team 1) is responsible for preparation and environment setting.

2) and the testing team (Team 5), which is responsible for welding joint polishing and magnetic work.

Team 5 is divided into two groups that hand off every 2 hours. The HRT scenario needs at least two robots inside the spherical tank, one for polishing and the other for magnetic purposes (Chen *et al.*, 2022). A typical robot used for the magnetic purpose is shown in Fig.5, controlled by operators outside the spherical tank.



1- Multifunctional lifting handle;
2- Outer frame;
3- Electric circuit box;
4- Multifunctional rear handle;
5- Universal wheel;
6- Magnetic buffer device;
7- Body bracket;
8- Drive rubber wheel;
9- Magnetic adsorption unit.

Figure 5 The basic structure of the polishing or magnetic robot (Chen *et al.*, 2022)

3.2 System characteristics definition

Through the interview with stakeholders, the main objective of the spherical tank inspection activity was defined: to detect the early fault correctly while considering occupational safety and time duration. Therefore, system goals could be summarized in safety, efficiency, and accuracy, identifying also the related consequences in case of malfunctions:

1) occupational accident,
2) time delay,
3) and wrong results.

3.3 Integrated task analysis

The FM inspection process includes the following five operational tasks and an emergency operation.

1) FM Task 1: Preparation and environment setting (subtasks 1.1~1.10)
2) FM Task 2: Scaffold building (subtasks 2.1~2.9)
3) FM Task 3: Manual polishing (subtasks 3.1~3.9)
4) FM Task 4: Manual magnetic and crack identification (subtasks 4.1~4.12)
5) FM Task 5: Scaffold dismantle (subtasks 5.1~5.7)
6) FM Task 6: Emergency management (subtasks 6.1~6.3)

The detailed analysis of the 50 subtasks is shown in the Annex, as Table A.3.

The HRT inspection includes three operational tasks and an emergency operation.

1) HRT Task 1: Preparation and environment setting (subtasks 1.1~1.10)
2) HRT Task 2: HRT polishing (subtasks 2.1~2.15)
3) HRT Task 3: HRT magnetic and crack identification (subtasks 3.1~3.18)
4) HRT Task 4: Emergency management (subtasks 4.1~4.3)

The detailed analysis of 45 subtasks is shown in the Annex, as Table A.4.

3.4 Human reliability estimates

Based on the integrated task analysis, the functions and failure modes of human activities were identified. The nominal probability value of the cognitive failure mode have been estimated based on Table A.1. Then, the CPCs are evaluated. In this case study, five teams are needed to set CPCs, as mentioned in Section 3.1. Based on the basic information of the five teams, five experts with more than 10 years of experience in chemical engineering and human factors were invited to assess the weight of CPC levels. Through Equations (2) and (3), the evidence from five experts has been fused. The combined weights for each level are shown in the Annex, as Table A.5. After the multiplier was selected, combined with the nominal value, the failure rate of each cognitive function failure mode for each team was calculated, as shown in Table 4.

Table 4 The probability of each cognitive failure mode for five teams

	O1	O2	O3	I1	I2	I3	P1	P2	E1	E2	E3	E4	E5
Team1	1.60E-04	1.12E-02	1.12E-02	2.50E-02	1.25E-03	1.25E-03	5.00E-04	5.00E-04	3.84E-04	3.84E-04	6.40E-05	3.84E-02	3.84E-03
Team2	2.00E-04	1.40E-02	1.40E-02	2.50E-02	1.25E-03	1.25E-03	1.25E-03	1.25E-03	6.00E-04	6.00E-04	1.00E-04	6.00E-02	6.00E-03
Team3	4.00E-04	2.80E-02	2.80E-02	2.50E-02	1.25E-03	1.25E-03	6.25E-03	6.25E-03	1.20E-03	1.20E-03	2.00E-04	1.20E-03	1.20E-02
Team4	1.00E-04	7.00E-03	7.00E-03	2.50E-02	1.25E-03	1.25E-03	1.25E-03	1.25E-03	3.00E-04	3.00E-04	5.00E-05	3.00E-02	3.00E-03
Team5	2.00E-04	1.40E-02	1.40E-02	2.50E-02	1.25E-03	1.25E-03	1.25E-03	1.25E-03	6.00E-04	6.00E-04	1.00E-04	6.00E-02	6.00E-03

3.5 Robot reliability estimates

The basic robot function failure rates are estimated according to Table 3. In addition, the average performance metric for the crack identification algorithm was considered as 90% as initial identification precision and 99% the identification rate on recalls. The definitions of Precision and recall are(Olson & Delen, 2008):

$$Precision = \frac{tp}{tp+fp} \tag{4}$$

$$Recall = \frac{tp}{tp+fn} \tag{5}$$

Where *tp* represents the number of true positive results, *fp* represents the number of false positive results, and *fn* represents the number of false negative results.

3.6 System performance qualitative analysis

Initial results from the qualitative analysis allowed a better understanding of the communication modes between robots and operators in the HRT operations and how the interaction mode changes between the FM and HRT operations in terms of both scenarios and of cognitive functions involved.

Several communication modes (direct physical interaction, remote contactless interaction, teleoperation, and message exchange) and interaction modes (coexistence, synchronized, cooperation, collaboration) are acknowledged (Hashemi-Petroodi *et al.*, 2020); according to the integrated task analysis, the human-robot communication modes and interaction modes are summarized in Table 5 and Table 6.

Table 5 The human-robot communication modes

Communication mode	Scenario
Direct physical interaction	The technician removes iron pieces from the polishing robot;
Remote contactless interaction	Robots send an alarm to alert the technician;
	The magnetic robot waits for confirmation of the identified crack;
	The technician monitors robots;
Teleoperation	The technician controls the robots to the right paths remotely;
Message exchange	The technician set the robot parameters;

Table6 The human-robot interaction modes

Interaction mode	Scenario
Synchronized (in different places)	The magnetic robot and the technician perform the crack identification task. The robot first identifies the crack and stops to send an alarm to the technician. Then, the technician detects the alarm and confirms or denies the crack identification decision.
Collaboration	The technician removes iron pieces from the polishing robot. The technician and robot perform the polishing task together.

Goodrich & Schultz (2008) propose the concept of dynamic interaction as a characterization that incorporates all five dimensions Human-Robot Interface designers can intervene on, namely autonomy, how information is exchanged, team structure, learning and training of the humans and robots involved, and the shape of the task. The changes HRI brings to the system in this case are summarized in Table 7.

Table 7 The human-robot interaction changes

	Team structure	Communication type	Human role	Task demand Cognitive function
FM	5 teams	Multi-team communication. Inter-team communication;	Single role as operator or supervisor	More executions
HRT	2 teams	Inter-team communication. Human-robot communication	Multi roles as both operator and supervisor	More Interpretation and plan

These qualitative results could be of support in optimizing the operation design and planning.

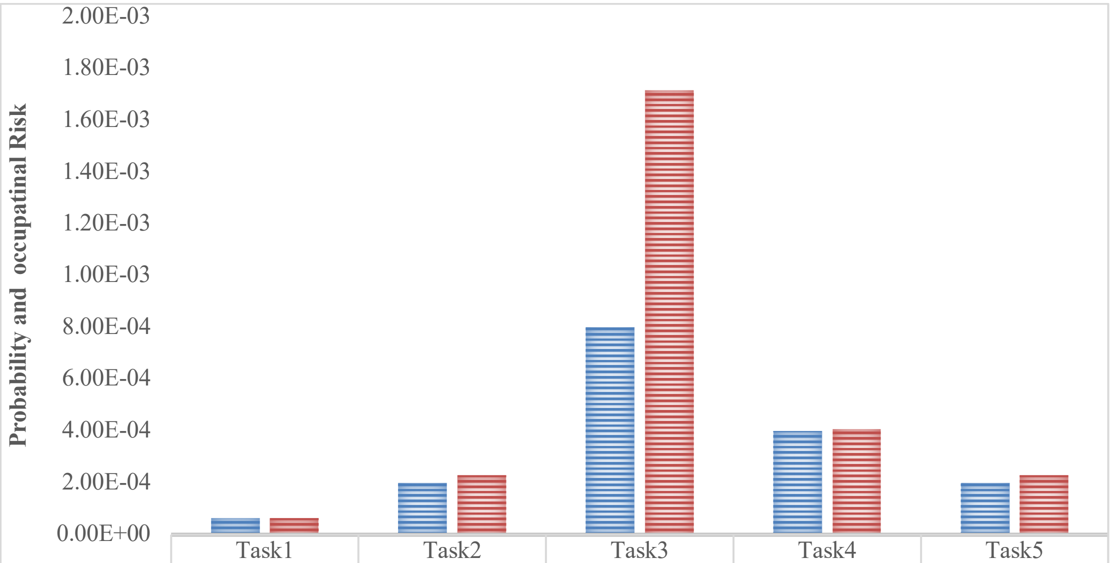
3.7 System performance quantitative analysis based on IDDA

In the following, the quantitative results of the case study are discussed. The elaboration of the input file of IDDA brought to the identification of all the sequences of events the systems can undergo, characterized by their probability of occurrence and their consequence, allowing direct visualization of risks.

To quantify the consequences, specific indexes were adopted. For the occupational accident, the following indexes were used: Minor cuts, bruises, and bumps at 1. Disabling injuries at 5. Extremely serious at 15, Fatality at 25, Multiple fatalities at 50, and Catastrophe at 100 (Fine, 1970). Time delays were quantified through the real delay time duration in terms of days. An example of an IDDA input file is shown in Annex B.1, and the examples of IDDA outputs for a single event tree and complete event trees for HRT occupational accident risk are shown in Annex B.2 and Annex B.3. The outputs include the probability and risk for every main task and subtask (as mentioned in 3.3). The results are discussed in the following paragraphs.

3.7.1 The system performance in the FM scenario

Fig.6 shows the values of occupational incident risk in the FM scenario. Task 3(Manual polishing) has the highest probability of occurrence at 8.00E-04 and risk at 1.72E-03, followed by Task 4 (Manual magnetic and crack identification). Among all the subtasks, the object or personnel that fell from high has the highest risk at 1.43E-03 (Occupational failure risk of subtask 2.5, 2.6, 3.5, 3.6, 4.6,4.7,4.8,4.9, and 4.10 in Table A.3). A spark from polish hurt the operator's eye at 9.61E-04 (Occupational failure risk of subtask 3.6 in Table A.3). And then the third highest occupation incident risk is ultraviolet rays that hurt the operator's eye at 2.76E-04 (Occupational failure risk of subtask 4.9 in Table A.3).



	Task1	Task2	Task3	Task4	Task5
Probability	6.40E-05	2.00E-04	8.00E-04	4.00E-04	2.00E-04
Risk	6.42E-05	2.30E-04	1.72E-03	4.09E-04	2.29E-04

Figure 6 The occupational incident probability and risk for FM main tasks.

Fig.7 shows the values of time delay risk in the FM scenario. Task 2 (Scaffold building) has the highest risk at 4.30E-03, with the third highest probability at 8.00E-04. Among subtasks, fixing the unstable scaffold has the highest risk at 3.67E-03 (Time delay failure risk of subtasks 2.8 and 2.9 in Table A.3). Repolishing the weld joints operation risk is at 1.22E-03(Time delay failure risk of subtasks 3.8 and 3.9 in Table A.3). Moreover, the third risky delay subtask is reventilating the spherical tank with risk at 1.02E-03 (Time delay failure risk of subtasks 1.6 and 1.8 in Table A.3).

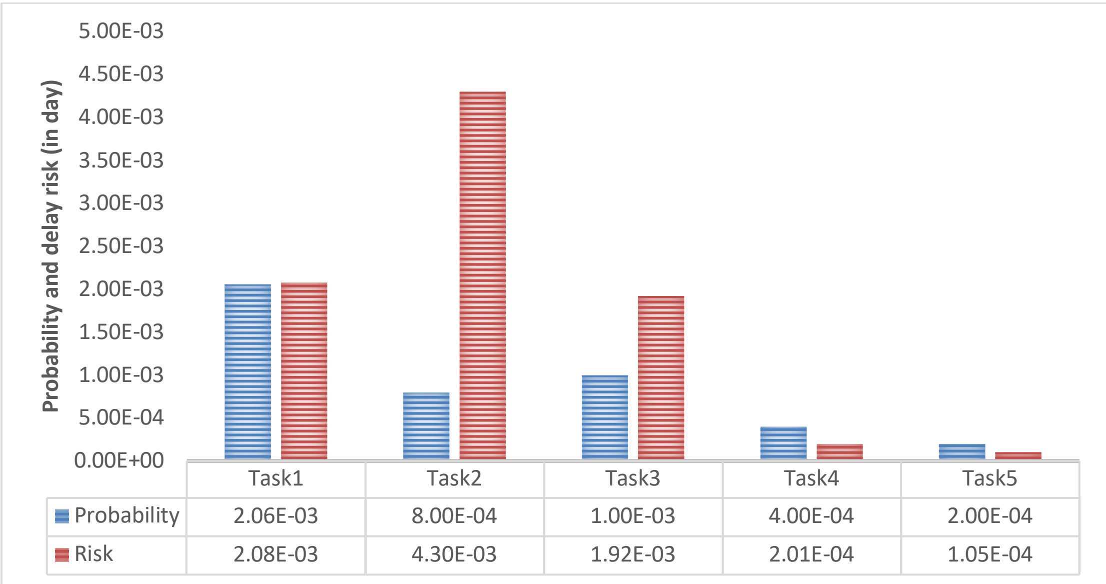


Figure 7 The delay probability and risk for FM main tasks

Only Task 3(Manual polishing) and Task 4(Manual magnetic and crack identification) may lead to the wrong result of the crack identification, with the total probability at 1.53E-02. The most contributing subtask is humans identifying the crack wrongly (Wrong result failure probability of subtasks 4.9 in Table A.3).

3.7.2 The system performance of the HRT scenario

Fig.8 shows the values of occupational incident risk in the HRT scenario. Task 2(HRT polishing) and Task 3 (HRT magnetic and crack identification) have the same failure rate at 2.14E-04, followed by Task 1, which is the same in the FM scenario. Falling when climbing the ladder outside the tank has the highest risk at 2.24E-04 (Occupational accident failure risk of subtasks 2.6 and 3.6 in Table A.4); adopting a safety rope and helmet could reduce the risk to 1.95E-04(Subtasks 2.2 and 3.2 in Table A.4). Getting shocked when connecting the robot to electricity is the second occupational safety critical operation scenario, with the risk at 1.96E-04 (Occupational accident failure risk of subtasks 1.5, 2.5, and 3.5 in Table A.4).

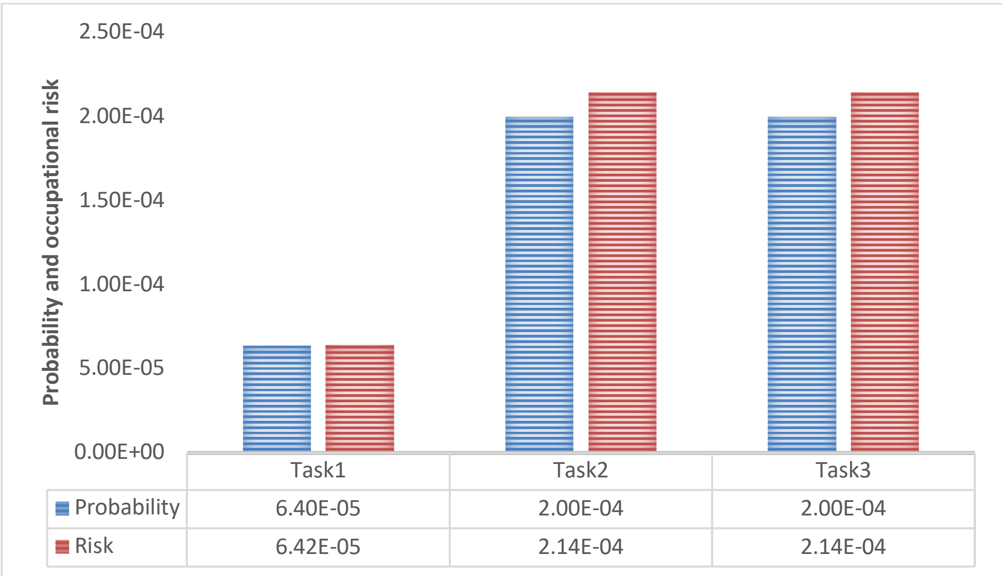
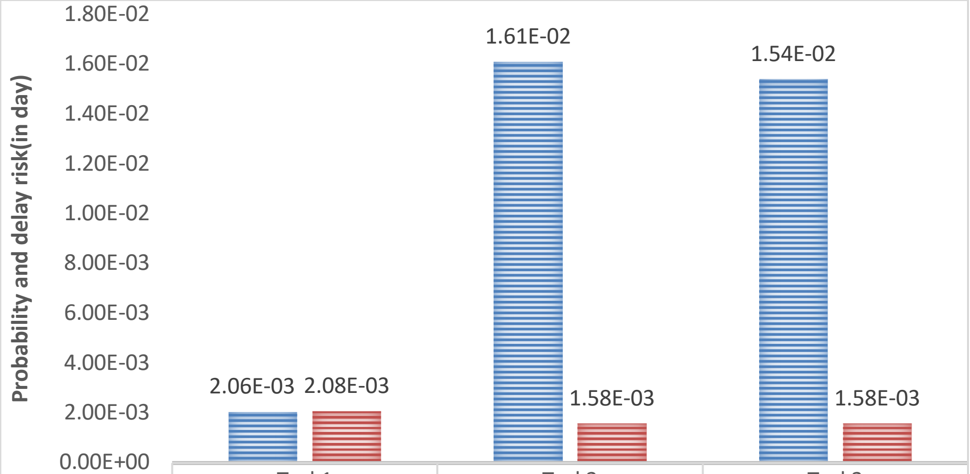


Figure 8 The occupational incident probability and risk for HRT main tasks

Fig.9 shows the values of time delay risk in the HRT scenario. Task 1, the same as the FM scenario, has the highest risk, with the lowest probability at 2.06E-3. Task 2 (HRT polishing) and Task 3 (HRT magnetic and crack identification) have a slightly lower failure risk at 1.58E-03.



	Task1	Task2	Task3
Probability	2.06E-03	1.61E-02	1.54E-02
Risk	2.08E-03	1.58E-03	1.58E-03

Figure 9 The delay probability and risk for HRT main tasks

The failure rate of the HRT system to get the wrong result of crack identification was 1.58E-03. Not cleaning the iron pieces in time contributes most to the delay and the risk of wrong results in HRT operations (Subtask 2.15 in Table A.4). This is followed by the operator refusing the robot's decision, which has correctly identified a crack (Subtask 3.18 in Table A.4).

3.7.3 The system performance comparison of two scenarios

Fig.10 shows the system performance comparison of the FM and HRT scenarios. The HRT system shows lower occupational incident probability and risk, at the values 4.64E-04 and 4.93E-04, nearly five times less than the FM system. Also, the HRT system has less delay risk than the FM system at 5.24E-03, although with a higher delay probability at 3.36E-02. This difference means the HRT system may have more delay scenarios, but the overall delay time is less than the FM system. However, the probability of getting the wrong result of the HRT system is higher than for fully manual operations, at 3.35E-02.

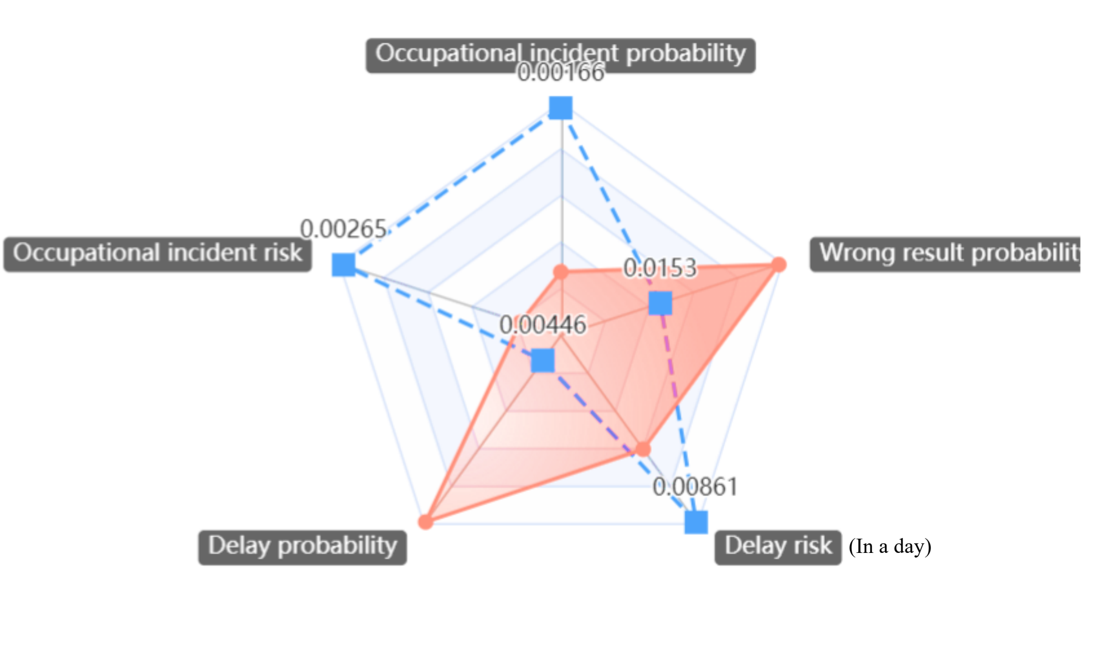


Figure 10 The system performance comparison of FM and HRT scenarios

4 Discussions and implications

The two scenarios of the pressure spherical tank inspection case show that the proposed integrated framework can do qualitative and quantitative analysis for the complex socio-technical system performance.

Compared to the HRT design framework proposed by Borges *et al.* (2021), that was mainly focused on applying scale tools in ergonomics, the framework proposed in this research emphasizes the integrated task analysis, considering the cognitive functions and the function interdependencies. In this way, the case study shows a more detailed logical foundation for the quantitative analysis. Based on qualitative analysis results, as shown in Table 5~7, the most essential communication type of HRT is human-robot communication. Thus, the performance of the HRT system is deeply impacted by human's rational trust in robots (Lee & See, 2004). Wang *et al.* (2015) designed a simulated experiment to let a robot express its algorithm accuracy values to the human teammate through natural language to aid human decision-making on whether to trust a robot's judgment. This expression method could be an alternative to enhance information transparency in the process of crack identification: the robot could communicate precision and recall to the operators, but also a judgment on the accuracy of the result. For example, the robot gives the crack judgment and the message, "I believe this is a crack, but I may be false true at 10%". This dialogue could aid human teammates in better informative decision-making.

Based on quantitative analysis results for the FM system risk assessment, the most contributing factor to occupational accidents in the inspection process is "fall from height". These results are consistent with previous literature (Dogan *et al.*, 2021).The overall human failure rate of scaffolding work was estimated as 4.30E-03 (X. Li *et al.*, 2023). In this research, the total failure rate of task 2 (Scaffold building) is at 4.73E-03 (combining the time delay and occupational accident probability). Our results are higher for this research considering the inside tank hazards. This similarity of results is a validation of the effectiveness of this framework.

The comparison of quantitative results showed that the HRT scenario reduced the occupational risk because robots worked in an extreme environment instead of humans. However, the downside of this change may lead to the loss of some precision of the crack identification. The task most contributing to the overall failure probability of the wrong result in the HRT operation scenario is "detecting the iron pieces cumulated in the polish robot." In the previous HRT operation design, this detection function was based on the time interval estimate and the robot body's radiation identification. The optimized suggestion in the HRT system design is to add a function where the robot could self-identify the cumulated iron pieces and send an alarm with a salient sound and colored icon. The second contributing subtask is the operator refusing a decision of the robot, which has been correctly identified as a crack by the robot. This risk could be reduced by adding a second check by another technician. Under this circumstance, the overall failure probability of the wrong result in the HRT operation scenario would be reduced to about 7.52E-03, nearly half of that in the FM operation scenario, which will be superior to the FM system in nearly all aspects, other than the delay probability as shown in Fig.11. This is because the inspection robots are still in the testing stage which will have more failure scenario than the mature ones according to the bathtub cure (Klutke et al., 2003). Therefore, the HRT system promises better performance in all aspects in the long term.

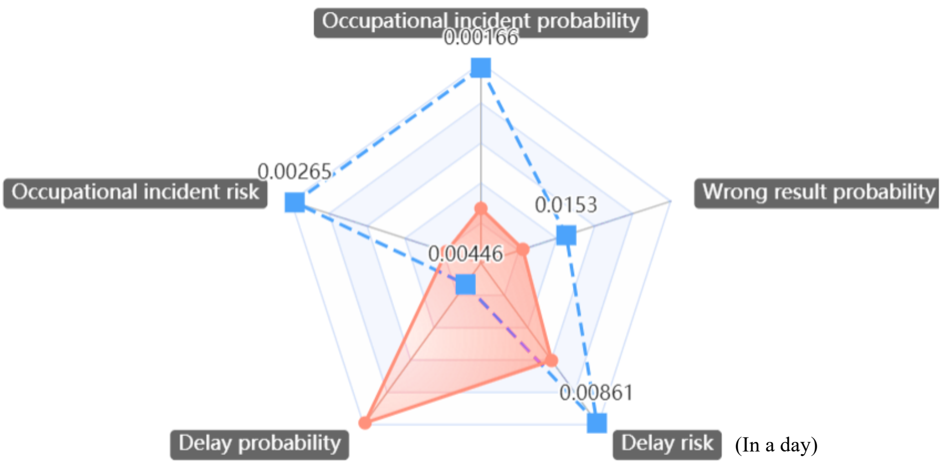


Figure 11 The system performance comparison of FM and HRT scenarios after optimization

One thing that needs to be highlighted is that these results are based on the performance metric of the crack identification algorithm precision at 90% and recall at 99%. These values are a recommended balance trade-off of precise and recall values for the lowest requirement for the performance of a crack identification algorithm that could be applied in real work. The quantitative analysis showed that a lower recall value will mean the recall rate will be lower than the human observation success rate. At the same time, a lower accuracy rate would introduce too long-time human checking work.

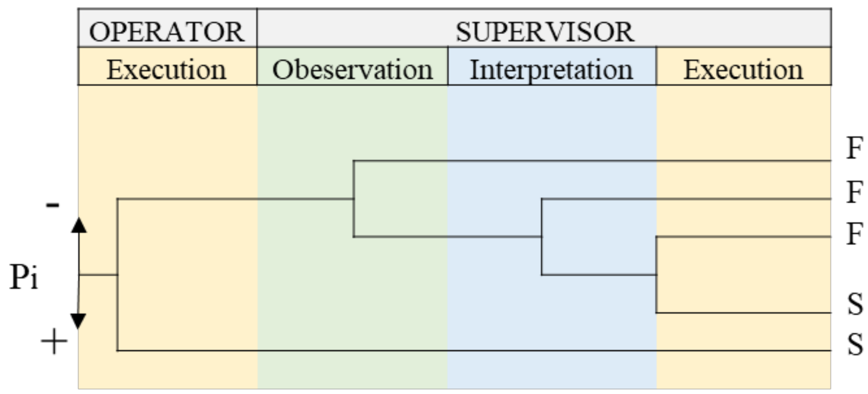
5 Conclusions

This study addressed the changing working environment in the process industry with the introduction of robots, especially in terms of Human-Robot Teaming (HRT) performance and risk assessment. An integrated framework was proposed based on Task analysis, IDDA, and the DST extended CREAM to keep into account not only the technical elements but also the human and organizational ones. The outputs demonstrated that the integrated framework well represented both the Fully Manual (FM) and HRT system performance measurement, generating knowledge that can be exploited to reduce the system's risk and choose among different operational alternatives. The main changes after introducing robots into maintenance processes are reduced occupational risk but a loss of precision in the inspection results.

Very few studies focused on integrated HRT system performance assessment in chemical industry operations. Therefore, this research aims to fill the gap by conducting a comprehensive system performance analysis concerning the changes from FM to

HRT systems in pressurized tank inspection operations. The composite framework overcomes the recognized shortcomings in risk assessment for the HRT system in a qualitative and quantitative integrated way of organizational, human cognitive, and technical factors, also considering their interdependencies. The proposed framework has been examined in detail and provides valuable perspectives for decision-makers of pressurized tank inspection institutes, safety departments in chemical companies, and safety researchers, but it can be extended to assess the systems' performance whenever HRT is concerned.

Some limitations must be highlighted: this work used robot reliability data from the regulation requirements and literature data. This data source can lead to quite a conservative estimate compared to practical industry applications. In the human reliability estimate part, some operations were long-term lasting other than just one activity performed quickly, such as polishing in the spherical tank. The CREAM method does not consider the difference in actions in performing time duration. That means giving the same failure rate for polishing for two hours or two minutes. This ignorance needs a dynamic method to tackle this problem. More detailed teams' function analysis, such as (supervisor and operators) as Fig.12 shows, could be integrated in future work.



- Pi is the initial error probability; F represents the Failure state, and S represents the Success state.

Figure 12 The event tree for supervisor-operator team with cognitive function

Thus, further studies are expected to overcome these limitations and further test the framework for other applications.

CRediT authorship contribution statement

Shuo Yang: Writing – original draft, Methodology, Data curation, Conceptualization. **Micaela Demichela:** Writing – review & editing, Supervision. **Jie Geng:** Visualization, Investigation. **Ling Wang:** Resources. **Zhangwei Ling:** Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Shuo yang reports financial support was provided by China Scholarship Council. Shuo yang reports financial support was provided by the Natural Science Foundation of Zhejiang Province, China. Shuo yang reports a relationship with China Scholarship Council that includes funding grants.

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Annex A

Table A.1 The cognitive activity matrix with cognitive function(Hollnagel, 1998)

Activity	Cognitive function			
	Observation	Interpretation	Planning	Execution
Coordinate			*	*
Communicate				*
Compare		*		
Diagnose		*	*	
Evaluate		*	*	
Execute				*
Identify		*		
Maintain			*	*
Monitor	*	*		
Observe	*			
Plan			*	
Record		*		*
Regulate	*			*
Scan	*			
Verify	*	*		

Table A.2 The weighting factor for CPCs(Hollnagel, 1998)

CPCs name	Level	COCOM function modifier value			
		OBS	INT	PLAN	EXE
Adequacy of organization	Very efficient	1.0	1.0	0.8	0.8
	Efficient	1.0	1.0	1.0	1.0
	Inefficient	1.0	1.0	1.2	1.2
	Deficient	1.0	1.0	2.0	2.0
Working conditions	Advantageous	0.8	0.8	1.0	0.8
	Compatible	1.0	1.0	1.0	1.0
	Incompatible	2.0	2.0	1.0	2.0
Adequacy of MMI and operational support	Supportive	0.5	1.0	1.0	0.5
	Adequate	1.0	1.0	1.0	1.0
	Tolerable	1.0	1.0	1.0	1.0
	Inappropriate	5.0	1.0	1.0	5.0
Availability of procedures/plans	Appropriate	0.8	1.0	0.5	0.8
	Acceptable	1.0	1.0	1.0	1.0
	Inappropriate	2.0	1.0	5.0	2.0
Number of simultaneous goals	Fewer than capacity	1.0	1.0	1.0	1.0
	Matching current capacity	1.0	1.0	1.0	1.0
	More than capacity	2.0	2.0	5.0	2.0
Available time	Adequate	0.5	0.5	0.5	0.5
	Temporarily inadequate	1.0	1.0	1.0	1.0
	Continuously inadequate	5.0	5.0	5.0	5.0
Time of day	Daytime(adjusted)	1.0	1.0	1.0	1.0
	Nighttime(unadjusted)	1.2	1.2	1.2	1.2
Adequacy of training and preparation	Adequate, high experience	0.8	0.5	0.5	0.8
	Adequate, low experience.	1.0	1.0	1.0	1.0
	Inadequate.	2.0	5.0	5.0	2.0
Crew collaboration quality	Very efficient	0.5	0.5	0.5	0.5
	Efficient	1.0	1.0	1.0	1.0

	Inefficient	1.0	1.0	1.0	1.0
	Deficient	2.0	2.0	2.0	5.0

Table A.3 A list of subtasks and dependencies for the FM inspection process

NO.	Subtasks	Actor	Location	CFM	Hazard	Input	Output	D	W	O
1.1	Make the inspection plan	Technician supervisor1	Office room	P2			Plan			
1.2	Check the inspection plan	Technician supervisor2	Office room	O2, I1		1.1	Plan	*		
1.3	Insert the blind disc	Plant Operator1	Outside tank	E1			Isolation state			
1.4	Check the isolation	Plant Operator2	Outside tank	O2, I1		1.3	Isolation state	*		
1.5	Electricity environment setting	Plant Operator1~2	Manhole	E3	Electricity shock		Electricity environment	*		*
1.6	Start and keep venting for 3 days	Plant Operator1	Manhole	E2	Flammable gas		Ventilation finished	*		*
1.7	Take the air sample	Plant Operator1	Manhole	E1			Air sample			
1.8	Test the air concentration	Plant lab	Plant lab	E1		1.7	Air component concentrate	*		
1.9	Perform the safety training	Plant safety manager	Outside tank	E5			Trained operators			
1.10	Authorize the inside inspection work	Plant safety manager	Office room	O2, I1	No permit	1.8	Inspection Permit	*		*
2.1	Check all materials and tools availability	Construction supervisor1	Outside tank	E5			Qualified tools			
2.2	Wear PPE	Construction group1	Outside tank	E5			Protected state			
2.3	Test the air concentration	Construction supervisor1	Manhole	E1		2.1	Air component concentrate			
2.4	Enter the tank with a gas detector	Construction group1	Manhole	E5	Toxic flammable gas	2.3,2.2		*		*
2.5	Climb up ladder	Construction group1	Inside tank	E3	At height, low O2	2.2		*		*
2.6	Build the scaffold	Construction group1	Inside tank	E1	At height, low O2	2.2	Scaffold	*		*
2.7	Handoff to next shift after two hours	Construction group1	Manhole	E2	low O2			*		*
2.8	Check scaffold quality	Construction supervisor1~2	Inside tank	O2, I1		2.6	Scaffold qualified	*		
2.9	Cross-check scaffold quality	Plant safety manager	Inside tank	O2, I1		2.8		*		
3.1	Check all materials and tools	Polish supervisor1	Outside tank	E5			Qualified tools			
3.2	Wear PPE	Polish team1	Outside tank	E5			Protected state			
3.3	Test the air concentration	Polish supervisor1	Manhole	E1		3.1	Air component concentrate			
3.4	Enter the tank with a gas detector	Polish group1	Manhole	E5	Toxic flammable gas	3.2,3.3		*		*
3.5	Climb up scaffold	Polish group1	Inside tank	E3	At height, low O2	2.9		*		*
3.6	Polish the weld joint with a sander	Polish group1	Inside tank	E3	At height, low O2, sharp tool		Polished weld joints	*	*	*
3.7	Handoff to next shift after two hours	Polish group1	Inside tank	E2	low O2			*	*	*
3.8	Check polish quality	Polish supervisor1-2	Inside tank	O2, I1		3.6	Qualified polished joints	*		
3.9	Cross-check polish quality	Plant safety manager	Inside tank	O2, I1		3.8	Qualified polished joints	*		
4.1	Check all materials and tools	Technician supervisor1	Outside tank	E5			Qualified tools			
4.2	Perform magnetic liquid sensitivity test	Technician group1	Outside tank	E5			Qualified material			
4.3	Wear PPE	Technician group1	Manhole	E5		4.1	Protected state			
4.4	Test the air concentration	Technician supervisor1	Manhole	E1		4.1	Air component concentrate			
4.5	Enter the tank with a gas detector	Technician group1	Inside tank	E5	Toxic flammable gas	4.4		*		*
4.6	Climb up scaffold	Technician group1	Inside tank	E3	At height, low O2	2.11		*		*
4.7	Spray the liquid toward the weld joint	Technician1	Inside tank	E3	At height, low O2	3.11	Wet weld joints	*	*	*
4.8	Magnetic with X posture	Technician1	Inside tank	E1	At height, low O2	4.7	Magnetic patterns	*	*	*
4.9	Irradiate with UV light and identify a crack	Technician1	Inside tank	O2, I2	At height, low O2, hazard light	4.8	Marked cracks	*	*	*
4.10	Mark the crack	Technician1	Inside tank	E3				*	*	*

4.11	Handoff to next shift after two hours	Technician group2	Inside tank	E2				*		
4.12	Self-check identified cracks	Technician supervisor1-2	Inside tank	O2, I1			Confirmed cracks	*		
5.1	Check all materials and tools	Construction supervisor1	Manhole	E5			Qualified tools			
5.2	Wear PPE	Construction group1	Manhole	E1		5.1	Protected state			
5.3	Test the air concentration	Construction supervisor1	Inside tank	E1		5.1	Air component concentrate			
5.4	Enter the tank with a gas detector	Construction group1	Inside tank	E5	Toxic flammable gas	5.3		*		*
5.5	Climb up ladder	Construction group1	Outside tank	E3	At height, low O2			*		*
5.6	Dismantle the scaffold	Construction group1	Manhole	E3	At height, low O2			*		*
5.7	Handoff to next shift after two hours	Construction group1	Inside tank	E2	low O2			*	*	*
6.1	Detect the low O2 alarm	Plant operators	Manhole	O3, I1						
6.2	Perform rescue procedures	Plant safety manager	Office room	P2, E2		1.2				
6.3	Check inside members are safe every 15min	Plant safety manager	Outside tank	E5						

- D: represents time delay risk
- W: represents wrong results risk
- O: represents occupational accident risk

Table A.4 A list of subtasks and dependencies for the HRT inspection process

NO.	Subtask	Actor	Location	CFM	Hazard	Input	Output	D	M	O
1.1	Make the inspection plan based on reports	Technician 1	Office room	P2			Plan			
1.2	Check the inspection plan	Technician 2	Office room	O2, I1		1.1	Plan	*		
1.3	Insert the blind disc	Plant operator1	Outside tank	E1			Isolation state			
1.4	Check the isolation	Plant operator2	Outside tank	O2, I1		1.3	Isolation state	*		
1.5	Electricity environment setting	Plant operator1~2	Manhole	E3	Electricity shock		Electricity environment	*		*
1.6	Start and keep venting for three days	Plant operator1	Manhole	E2	Flammable gas		Ventilation finished	*		*
1.7	Take the air sample	Plant operator1	Manhole	E1			Air sample			
1.8	Test the air sample	Plant lab technician1	Plant lab	E1		1.7	Air component concentrate	*		
1.9	Perform the safety training	Plant safety manager	Outside tank	E5			Trained operators			
1.10	Authorize the inside inspection work	Plant safety manager	Office room	O2, I1	No permit	1.8	Inspection Permit	*		*
2.1	Check all materials and tools	Technician group 1	Outside tank	E5			Qualified tools			
2.2	Wear PPE	Technician group1~2	Outside tank	E5		2.1	Protected state			
2.3	Test the air concentration	Technician group1	Manhole	E1		2.1	Air component concentrate			
2.4	Enter the tank with a gas detector	Technician group1	Manhole	E5	Toxic flammable gas	2.3		*		*
2.5	Connect the robot with electricity	Technician group1	Manhole	E3	Electricity shock		Robot with electricity	*		*
2.6	Climb the ladder and at the manhole	Technician group2	Outside surface	E3	At height			*		*
2.7	Connect the p-robot with a safety rope	Technician group2	Manhole	E1			Robot protected			
2.8	Set the p-robot parameters	Technician group1	Outside tank	O2, E3			Robot set		*	

2.9	Start and monitor the polish robot	Technician group1	Office room	O2, I1			Robot started	*	*	
2.10	Handoff to next shift after two hours	Technician group1	Office room	E2						
2.11	P-robot moves along the weld joint	P-robot	Inside tank	E1		2.8		*	*	
2.12	P-robot polishes with proper force	P-robot	Inside tank	E1		2.8	Polished joints	*	*	
2.13	P-robot videos of the Polish process	P-robot	Inside tank	O3		2.8	Video record	*	*	
			Office room			2.11,2.12,2.1				
2.14	Recovery from the wrong situation	Technician group1		O2, I1, P2, E3		3		*		
2.15	Clean the iron pieces cumulated on p-robot	Technician group1	Manhole	O3			Robot cleaned	*	*	
3.1	Check all materials and tools	Technician group2	Outside tank	E5			Qualified tools			
3.2	Wear PPE	Technician1~4	Outside tank	E5		3.1	Protected state			
3.3	Test the air concentration	Technician1~4	Manhole	E1		3.1	Air component concentrate			
3.4	Enter the tank with a gas detector	Technician group1	Manhole	E5	Toxic flammable gas	3.3		*		*
3.5	Connect the robot with electricity	Technician group1	Manhole	E3	Electricity shock		Robot with electricity	*		*
3.6	Climb the ladder and at the manhole	Technician group2	Outside surface	E3	At height			*		*
3.7	Connect the magnetic robot with a safety rope	Technician group2	Manhole	E1			Robot protected			
3.8	Set the magnetic robot parameters	Technician group2	Inside tank	O2, E3			Robot set		*	
3.9	Start and monitor the magnetic robot	Technician group1	Office room	O2, I1			Robot stated			
3.10	Handoff to next shift after two hours	Technician group2	Office room	E2						
3.11	M-robot moves along the weld joint	M-robot	Inside tank	E1		3.8		*	*	
3.12	M-robot magnetics with proper speed	M-robot	Inside tank	E1		3.8	Magnetic joints	*	*	
3.13	M-robot videos of the magnetic process	M-robot	Inside tank	O3		3.8	Video record	*	*	
			Office room			3.11,3.12,3.1				
3.14	Recovery from the wrong situation	Technician group1		O2, I1, P2, E3		3		*		
3.15	M-robot identifies a crack	M-robot	Inside tank	O2, I2		2.14,3.14	Identified crack		*	
3.16	M-robot sends an alarm	M-robot	Inside tank	E5			Crack alarm		*	
3.17	Detect the alarm	Technician group1	Office room	O2, I1		3.16	Acknowledged alarm		*	
3.18	Confirm/deny the crack	Technician group1	Office room	O2, I1		3.17	Confirmed/denied crack		*	
4.1	Detect the low O2 alarm	Plant safety manager	Outside tank	O2			Acknowledged alarm			
4.2	Perform rescue procedure	Plant safety manager	Outside tank	P2, E2		1.2				

- D: represents time delay risk
- W: represents wrong results risk
- O: represents occupational accident risk
- P-robot: Polish Robot, M-robot: Magnetic Robot

Table A.5 The weight of CPCs levels for five teams

CPC name	Level	Team1	Team2	Team3	Team4	Team5
Adequacy of organization	Very efficient	0.7	0.26	0.22	0	0.25
	Efficient	0.3	0.74	0.78	1	0.75
	Inefficient	0	0	0	0	0
	Deficient	0	0	0	0	0
Working conditions	Advantageous	0	0	0	0	0
	Compatible	1	0.91	0.81	0.74	1
	Incompatible	0	0	0	0	0
Adequacy of MMI and operational support	Supportive	0	0	0	1	0
	Adequate	1	1	1	0	1
	Tolerable	0	0	0	0	0
	Inappropriate	0	0	0	0	0
Availability of procedures/plans	Appropriate	1	0	0	0	0
	Acceptable	0	1	0.09	1	0.69
	Inappropriate	0	0	0.91	0	0.31
Number of simultaneous goals	Fewer than capacity	0	0	0	0	0
	Matching current capacity	0.94	0.99	1	1	1
	More than capacity	0.06	0.01	0	0	0
Available time	Adequate	1	0.93	0.93	1	1
	Temporarily inadequate	0	0.07	0.07	0	0
	Continuously inadequate	0	0	0	0	0
Time of day	Daytime(adjusted)	1	1	1	1	1
	Night-time(unadjusted)	0	0	0	0	0
Adequacy of training and preparation	Adequate, high experience	1	1	1	1	0.73
	Adequate, low experience	0	0	0	0	0.27
	Inadequate	0	0	0	0	0
Crew collaboration quality	Very efficient	0	0	0	0	0
	Efficient	1	1	1	1	1
	Inefficient	0	0	0	0	0
	Deficient	0	0	0	0	0

Annex B

B.1 IDDA input file example

```
! Task 2 Inspection team Polishing Weld Joints with robot
200 1, 0.006, 1., 201 201, ' Check all material and tools availability' ' Yes' ' No'
P 200 1,211,0.006 1.
210 1, 0.006,1.,211 211, ' Testing before entering the tank using multi-gas detector ' 'Yes' 'No'
211 1, 0.00001,1.,201 212, ' Multi-gas detector give the wrong result ' 'No' 'Yes'
212 1, 0.006,1.,213 216, ' Enter the tank wearing oxygen aid and toxic-prevent equipment' 'Yes' 'No' ! Occupation accident
216 1, 0.0112, 1., 217 218, 'Detect emergency ' 'Yes' 'No'
217 1, 0.000884, 1., 231 218, 'Perform rescue procedure in time' 'Yes' 'No'
L 217 0, 231 1
L 217 0, 233 1
218 1, 0, 1., 231 230, 'Serious suffocation accident' 'No' 'Yes'
L 218 1, 231 1
L 218 1, 233 1
213 1, 0.006,1.,201 230, ' Enter the tank wearing electrostatic-prevent cloth and shoes' 'Yes' 'No' ! Process accident
L 213 1, 232 1
L 213 1, 231 1
L 213 1, 233 1
201 1,0.0001,1., 203 230, 'Connect the robot with electricity get shock' 'No' 'Yes'
L 201 1, 231 1
L 201 1, 233 1
203 1,0.00135,1., 204 204, 'Set the robot parameters correctly' 'Yes' 'No'
L 203 1, 207 1
204 1,0.0001,1., 205 219, 'Climb the ladder at the manhole up' 'Yes' 'fall'
219 1, 0.006,1.,231 230, ' Wear safety rope' 'Yes' 'No'
L 219 0, 233 1
L 219 0, 231 1
L 219 1, 231 1
L 219 1, 233 1
205 1,0.0006,1., 206 206, 'Connect the robot with safety rope stable' 'Yes' 'No'
L 205 1, 221 1
206 1,0.00000246,1., 207 215, 'p-robot move along the joints' 'Yes' 'No'
207 1,0.00000198 , 1., 208 215, 'Polished weld joint properly force' ' Yes ' 'No'
208 1,0.00000048,1., 209 215, 'p-robot video the polish process' 'Yes' 'No'
L 208 1, 215 1
215 1,0.0256 , 1., 209 209, 'detect and Repolish' 'Yes ' 'No'
L 215 0, 233 1
L 215 1, 214 1
209 1,0.00000246, 1., 225 226, 'p-robot send an alarm with iron pieces' ' Yes ' 'No'
L 209 1, 226 1
225 1,0.014 , 1., 226 226, 'Detect the iron pieces alarm in time' ' Yes ' 'No'
L 225 1, 226 1
226 1,0.0006 , 1., 227 227, 'Clean the iron pieces in time' ' Yes ' 'No'
L 226 1, 214 1
227 1,0.00000002 , 1., 214 221, 'p-robot fall' ' No ' 'Fall'
221 1,0, 1., 214 230, 'the p-robot locked with protect rope' 'Yes' 'No'
L 221 0, 233 1
L 221 1, 230 1
L 221 1, 233 1
214 1,0,1., 230 230, 'p-robot polish the joints qualify' 'Yes' 'No'
L 214 1, 234 1
L 214 1, 334 1
230 1,0,1., 231 231, ' T2 robot or tank damaged' 'No' 'Yes'
L 230 1, 235 1
```

L 230 1, 1000 1
A 230 1, 235 * 1000
231 1,0,1., 232 232, ' T2 Occupation accident' 'No' 'Yes'
L 231 1, 235 1
L 231 1, 1001 1
A 231 1, 235 * 1000
232 1,0,1., 233 233, 'T2 Process accident' 'No' 'Yes'
L 232 1, 235 1
L 232 1, 1002 1
A 232 1, 235 * 1000
233 1,0,1.,234 234, ' T2 Delay' 'No' 'Yes'
L 233 1, 235 1
L 233 1, 1003 1
234 1,0,1.,235 235, ' T2 Wrong Result' 'No' 'Yes'
L 234 1, 235 1
L 234 1, 1004 1
235 1,0,1., 300 300, ' T2 Failure' 'No' 'Yes'
L 235 1, 1005 1

B.2 IDDA output example single event tree

Sequence probability				1.80E-04
Sequence consequence value				0.5
Sequence risk value				9.02E-05
Level	Out	Probability	Cumulative T. Factor	Mission T. Description
100	#0		1	The spherical tank inside is empty and purged Yes
154	0	1-1.25E-03	9.99E-01	Make an inspection plan that includes emergency procedures Yes
102	0	1-3.84E-04	9.98E-01	Insert the blind disc Yes
103	#0		0.9984	Open the manhole Yes
104	0	1-6.40E-05	9.98E-01	Set up electricity environment get shocked No
157	0	1-1.00E-05	9.98E-01	The ventilation machine is broken. No
105	0	1-3.84E-04	9.98E-01	Venting with venting machine for more than 3 days Yes
106	#0		0.9979	The inside air is safe Yes
107	#0		0.9979	The safety manager authorizes the inside work Yes
131	#0		0.9979	T1 Occupation accident No
132	#0		0.9979	T1 Process accident No
133	#0		0.9979	T1 Delay No
135	#0		0.9979	T1 Failure No
200	0	1-6.00E-03	9.92E-01	Check all material and tools availability Yes
201	0	1-6.00E-03	9.86E-01	Enter the tank through a manhole with a gas detector Yes
215	0	1-1.00E-05	9.86E-01	Ventilation machine broken No
203	0	1-2.00E-04	9.86E-01	Object fall down or Personnel Fall No
204	0	1-6.00E-04	9.85E-01	Build scaffold stable Yes
231	#0		0.9852	T2 Occupation accident No
232	#0		0.9852	T2 Process accident No
233	#0		0.9852	T2 Delay No
235	#0		0.9852	T2 Failure No
300	0	1-1.20E-02	9.73E-01	Check all material and tools availability Yes
301	0	1-1.20E-02	9.62E-01	Enter the tank through the manhole with a gas detector Yes
314	0	1-1.00E-05	9.62E-01	The ventilation machine is broken. No
303	0	1-4.00E-04	9.61E-01	Object fall down or Personnel Fall No
304	0	1-2.00E-04	9.61E-01	Spark from polish hurt eyes No
305	0	1-2.00E-04	9.61E-01	Get hurt by sander tool No
307	0	1-2.00E-04	9.61E-01	Polished weld joint qualified Yes
331	#0		0.9607	T3 Occupation accident No
332	#0		0.9607	T3 Process accident No
333	#0		0.9607	T3 Delay No
334	#0		0.9607	T3 Wrong Result No

335	#0		0.9607	T3 Failure No
400	0	1-1.20E-02	9.49E-01	Check all material and tools availability Yes
401	0	1-1.20E-02	9.38E-01	Enter the tank through manhole with gas detector Yes
414	0	1-1.00E-05	9.38E-01	The ventilation machine broken No
403	0	1-3.00E-04	9.37E-01	Magnetic with instrument according to the standard posture and time Yes
404	0	1-5.00E-05	9.37E-01	Spray fluorescence magnetic liquid towards the weld joints Yes
405	0	1-6.00E-04	9.37E-01	Irradiate the weld with ultraviolet rays correctly Yes
440	0	1-1.43E-02	9.23E-01	Miss a crack No
406	0	1-5.00E-05	9.23E-01	Mark the crack correctly Yes
441	0	1-5.20E-03	9.19E-01	False true a crack No
407	0	1-1.00E-04	9.19E-01	Object fall down or Personnel Fall No
408	0	1-3.00E-04	9.18E-01	Ultraviolet rays hurt eyes No
431	#0		0.9183	T4 Occupation accident No
432	#0		0.9183	T4 Process accident No
433	#0		0.9183	T4 Delay No
434	#0		0.9183	T4 Wrong Result No
435	#0		0.9183	T4 Failure No
500	0	1-6.00E-03	9.13E-01	Check all material and tools availability Yes
501	0	1-6.00E-03	9.07E-01	Enter the tank through manhole with a gas detector Yes
515	0	1-1.00E-05	9.07E-01	The ventilation machine broken No
503	1	2.00E-04	1.81E-04	Object fall down or Personnel Fall Yes
523	0	1-6.00E-03	1.80E-04	Wearing a safety helmet and rope Yes
531	#1		0.0001804	T5 Occupation accident Yes
532	#0		0.0001804	T5 Process accident No
533	#1		0.0001804	T5 Delay Yes
535	#1		0.0001804	T5 Failure Yes
1001	#1		0.0001804	Occupation accident Yes
1002	#0		0.0001804	Process accident No
1003	#1		0.0001804	Delay Yes
1004	#0		0.0001804	Wrong Result No
1005	#1		0.0001804	Failure Yes

B.3 IDDA output example complete event trees

a) HRT Task 1 occupational accident events:

Event sequences number : 68

Event probability : 6.40093e-05

Event mean consequence : 1.00238

Event risk : 6.41619e-05

Seq.N.	Event Tree N.	Probability	Consequence	Risk
1	16139	5.446971e-09	2.500000e+01	1.361743e-07
2	17458	8.619618e-11	2.500000e+01	2.154905e-09
……				
67	63993	1.928629e-14	1.000000e+00	1.928629e-14
68	63994	1.157622e-13	5.000000e+00	5.788109e-13

b) HRT Task 2 occupational accident events:

Event sequences number : 636

Event probability : 0.000199977

Event mean consequence : 1.072

Event risk : 0.000214375

Seq.N.	Event Tree N.	Probability	Consequence	Risk
1	3811	9.845407e-05	1.000000e+00	9.845407e-05
2	3812	5.942902e-07	2.500000e+01	1.485725e-05
……				
634	63931	2.722126e-19	1.000000e+00	2.722126e-19
635	63974	2.899121e-19	1.000000e+00	2.899121e-19
636	63976	2.920856e-19	1.000000e+00	2.920856e-19

c) HRT Task 3 occupational accident events:

Event sequences number : 5926

Event probability : 0.000199937

Event mean consequence : 1.072

Event risk : 0.000214332

Seq.N.	Event Tree N.	Probability	Consequence	Risk
1	117	9.622767e-05	1.000000e+00	9.622767e-05
2	118	5.808511e-07	2.500000e+01	1.452128e-05

……

5925	63960	2.833562e-19	1.000000e+00	2.833562e-19
5926	63962	2.854805e-19	1.000000e+00	2.854805e-19

a) HRT all occupational accident events:

Event sequences number : 6630

Event probability : 0.000463924

Event mean consequence : 1.06239

Event risk : 0.000492869

Seq.N.	Event Tree N.	Probability	Consequence	Risk
1	117	9.622767e-05	1.000000e+00	9.622767e-05
2	118	5.808511e-07	2.500000e+01	1.452128e-05

……

6629	63993	1.928629e-14	1.000000e+00	1.928629e-14
6630	63994	1.157622e-13	5.000000e+00	5.788109e-13

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