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# A methodological extension to human reliability analysis for cargo tank cleaning operation on board chemical tanker ships

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ABSTRACT

This is an article that conducts an empirical human reliability analysis for tank cleaning process on-board chemical tanker ship to enhance safety and operational reliability in maritime industry, providing a methodological extension through the integration of the AHP technique into the HEART approach. The paper provides a methodological development on decision making and human factors via extending a new approach to weight the proportion of the effect for calculating error producing conditions through operations. The model demonstration illustrates that cleaning of residues from hazardous cargoes such as acetic acid has required performing various critical tasks supported with recovery solutions. This research also provides practical insights along with reliability monitoring in ship operational level.



## 1. Introduction

In recent years, human factors have significantly increased in the marine industry since most of accidents have been widely caused by within shipboard hierarchy (Fortland, 2004). There have been various attempts proposed to tackle with human errors in order to enhance maritime safety. One of the most important attempts have been governed by IMO (International Maritime Organisation) whose aim is to establish a regulatory framework including safety, security, and pollution prevention in order to enhance maritime safety. In addition, maritime safety can be improved if the international regulatory requirements are effectively and systematically adopted by ship owners and shore-based management organisations continuously. Furthermore, majority of hazardous occurrences and marine accident caused by human error can seriously be reduced. In this sense, human performance and relevant conditions on-board ship play critical role to prevent marine accident particularly in tanker ships which are carrying dangerous cargo on-board.

The chemical tanker is special type of ships designed to carry petrochemical product cargoes in bulky condition. Since the petrochemical commodities shipping has been increasing enormously in marine transportation, their carriage requires extra attention due to the inherently hazardous content such as being poisonous, explosive, corrosive, and toxic (IMDG Code, 1996). These noxious products might have potential hazards for human life and marine environment whose control is required advance operating procedures supported with innovative marine technologies. Therefore, the carriage of the petrochemical substances is quite critical process includes serious tasks for responsible crew on-board ship. Particular attention has been given by ship crew during cargo operations such as loading, discharging, gas inerting, tank cleaning and gas freeing in shipboard platform engaged in the carriage of chemical cargoes. The IMO has recently adopted significant amendments for SOLAS (International Convention for the Safety of Life at Sea) convention which proposed new mandatory requirements for cargo tank cleaning and inerting. While carriage of chemical cargoes require excessively attentions, the crew must be well trained and qualified in both theoretical and practical manner as well as be aware of the potential hazards. Therefore, crew/human reliability on-board ship has been a serious concern in marine industry. The expectation from the crew is to perform system-required task without any misperception or violations which might cause an operational failure. So that, chemical tanker organisations should proactively control and prevent the possible catastrophe using advance techniques and smart procedures.

With this insight, this paper proposes a hybrid methodology to conduct HRA upon cargo tank cleaning operations on-board chemical tanker. The paper introduces a new approach by combining Analytic Hierarchy Process (AHP) methodology into HEART in order to provide comprehensive and rational framework for HRA.

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To achieve reasonable improvement in HEART approach, the paper is organized as follows; this section emphasized the role of the HRA in maritime safety. The next section provides literature review upon HRA. The third section identifies proposed methodology. Furthermore, an application on cargo tank cleaning operation onboard chemical tanker is presented to demonstrate the specific application of the proposed methodology in section four. The final sections give the discussion and conclusion as well as original contribution of the study.

## 2. Literature review

Human reliability is one of the significant aspects of shipboard operations since they have potential impacts on maritime safety. The consequences of human reliability directly affect marine environment, ship and commodity. The statistics show that human error is the most contributory factor to system failure and accident (Kirwan, 1987). In recent days, investigation of the human performance has been conducted as a core topic to minimise fatal accident in marine industry. Particularly, human reliability analysis has been a prominent subject for safety and reliability engineers, quality assurance specialists and ship operators since the shipboard organisations should have limited tolerance to operational and technical mistakes at sea.

Human reliability is defined as the probability that the person/operator performed system-required task without failure in a certain time period (Swain and Guttmann, 1983). The present HRA covers a couple of stages such as identifying human act, modelling of significant human action and evaluating human action probabilities. However, these methods have fundamental limitations to introduce all of the significant aspects of human performance due to insufficient data, subjectivity of analysis and uncertainty (Konstandinidou et al., 2006). The HRA utilises human error probability (HEP) values which is always difficult to find out. Therefore, the human reliability techniques focused on to solve HEP values with variety of applications.

Although the HRA is quite new disciplinary research, there have been numerous methods developed to quantify the human performance and calculate human error probability. The first generation HRA methods are covering the date between 1970–1990 years. The second generation is between 1990–2005 years. Consequently, the third generation HRA methods have been presented since 2005. As the human reliability has direct correlation with human factors, performance shaping factors (PSF) for human error came up to improve or reduce human performance (Blackman et al., 2008). In addition, PSF is sometimes called as common performance condition (CPC) or error producing conditions (EPC). The contribution of PSF into accident prevention leaded to emerge various HRA methods in literature.

The first HRA techniques were developed after the Second World War due to the substantial acceleration in military equipment such as weapon systems (Swain, 1990). Thereafter, numerous HRA approaches started to evolve in order to assess human error and reliability such as THERP (Technique for Human Error Rate Prediction). The method is hybrid and it combines the dependency and recovery (Swain, 1963). The purpose of the paper is to evaluate human reliability dealing with task analysis, failure definition and quantification of HEP values. To assess human failure in task or action sequences, SLIM (Success Likelihood Index Methodology), presented by Embrey et al. (1984), has been used to evaluate HEP occurring along the specific task. The method successfully applied in nuclear industry. Furthermore, Williams (1988) introduced a useful tool namely called HEART (Human Error Assessment and Reduction Technique) in order to analyse human tasks with identify HEP value by applying weighting factors. The HEART has been successfully modified and applied in numerous disciplines such as petrochemical industry (Noroozi et al., 2014), road transportation (Castiglia and Giardina, 2013), healthcare (Chadwick and Fallon, 2012) and nuclear energy (Kirwan, 1997). Furthermore, another HRA method, ATHEANA (A Technique for Human Error Analysis), was introduced as second generation technique in order to define human actions in nuclear industry (Cooper et al., 1996).

CREAM (Cognitive Reliability and Error Analysis Method) is another HRA technique introduced by Hollnagel (1998). This technique consists of basic and extended version. The basic version provides initial screening of human interaction while extended version utilises the findings of it in order to perform elaborative analysis. Likewise, Konstandinidou et al. (2006) proposed a different approach that combined the CREAM into a fuzzy logic in order to determine the human error actions probability. The paper offers a pilot model, which is successfully translating CREAM methodology into fuzzy logic. The authors use fuzzy logic in order to design CPC including nine input variables and one output variable. Another paper in which some developments were carried out in the fuzzy quantification of HEP in the light of the CREAM framework was presented by Marseguerra et al. (2006). The paper applied the proposed model into an emergency response to a steam generator tube rupture scenario in NPP (nuclear power plant).

SPAR-H (Standardized Plant Analysis Risk-Human reliability) technique was introduced by US Nuclear Regulatory Commission (NRC) in 1994. The purpose of this method is to define HEP values based on human performance influences. Thereafter, Bayesian network (Almond, 1992) method has been introduced as a new perspective (Jensen and Nielsen, 2007). Unlike traditional HRA approach, this approach contains the dependency between the different PSF and related actions in a direct way.

The HEART approach has numerous succeeded methodological extensions in the literature such as NARA (Nuclear Action Reliability Assessment), CARA (Controller Action Reliability Assessment) and RARA (Railway Action Reliability Assessment). These have recently been introduced as specific HRA methods. The NARA was introduced by Kirwan et al. (2004) as powerful tool to monitor human reliability performance in NPP. Likewise, the CARA was proposed by Kirwan and Gibson (2008) to assess HEP in aviation industry. A similar method RARA was developed by Gibson et al. (2012) for a specific approach to human error quantification in railway industry. Since those methods were derived from HEART, their unique parameters such as generic task type and error-producing conditions were re-defined in accordance with nuclear, aviation and railway industry respectively. Therefore, NARA, CARA and RARA methodologies have their own specific parameters.

Since HEART approach has successfully tailored in various disciplines, applications upon marine industry are scarce. For instance, Deacon et al. (2013) was introduced human error analysis to enhance offshore evacuation procedures. In the paper, authors utilize HEART methodology in order to determine HEP values for critical steps in the escape, evacuation and rescue process in offshore units. A similar methodological approach has been presented in recent days (Noroozi et al., 2014). In this paper, a condenser pump installed in single buoy moorings (SBM) in offshore platform has been analysed and HEP values have been evaluated during maintenance process. Furthermore, Montewka et al. (2010) introduced a new approach for collision probability modelling. The authors integrate Monte Carlo and generic models in order to conduct risk assessment for the case of collision at sea. Another HRA application on marine industry was a hybrid method combining APJE and SLIM (Xi and Guo, 2011). The aim of the paper is to predict marine HEP during ship to ship collision. Moreover, an illustrative example analysing cargo oil pump shut down scenario in oil tanker was applied by Yang et al. (2013). The paper introduces a modified

Fuzzy CREAM methodology integrated with Bayesian reasoning model. Likewise, the BN model has been applied to operational case (i.e. cargo oil spill) (Goerlandt and Montewka, 2014) where the article introduces BN method for reasoning under uncertainty to evaluate the collision case. Akyuz and Celik (2015) have recently introduced an article with regards to human reliability assessment upon cargo loading process on-board LPG tanker ships. The authors have applied CREAM basic and extended version to demonstrate the model.

## 3. Methodology proposal

This paper conducts an empirical human reliability analysis for tank cleaning process on-board chemical tanker ship to enhance safety and operational reliability in maritime industry by integrating HEART and AHP hybrid technique. The next section introduces both methodologies.

### 3.1. HEART approach

As the human error data is scarce in the literature, it is very difficult to use stochastic models such as Bayesian Network or Markov chain in maritime HRA concept to predict HEP value. Thus, using the empirical equation such as HEART seems more reasonable and sensible. The HEART is robust tool to compare the HEP values during reliability analysis. The technique is quick and flexible requiring few researches. It was presented to assess human tasks with defined values for HEP calculation (William, 1988). The basic fundamental is to depend on two parameters; the first one is generic task (GT) and second one is error producing condition (EPC). The GT allows user to find suitable task under HRA and then define the generic error probability (GEP) value (also known as nominal human unreliability), while EPC defines the PSF of human which influence the probability of human error in the related task. This means that EPCs are expected to affect human performance negatively and leading to increase HEP associated with generic tasks. The impact of GEP and EPC value were derived by numerous researches of human factor performances for a long time. These data base includes a variety of HEP values derived from numerous industries such as nuclear power plant, petrochemical industry, offshore platforms and service industry (William, 1988).

The method is easy to understand and the process starts with selecting a generic task type in order to employed GEP values as first parameter. There are totally eight generic tasks associated with eight GEP values which gives the probability of human error occurred in perfect condition. The analysts have specific tasks that they need to quantify during HRA. In order to do that, specific task is compared with GT by analysts and assigned respectively. Thereafter, EPC is nominated by experts as a second parameter. These are the factors (operator experience, familiarity with situation, time pressure, fatigue, noise level, etc.) that might heavily affect the human performance and increase the probability of human error. There are thirty-eight different EPCs assigned in HEART approach and seventeen of those have the substantial influence to HEP values (Kirwan et al., 1996). The selection of relevant EPC is usually based on scenario for the task being applied. EPC has a maximum nominal value which to be inserted in Eq. (1). The basic principles of HEART methodology are as follows; (i) Define the scenario, (ii) Nominate generic task type in accordance with scenario, (iii) Select GEP as per generic task, (iv) Define the relevant EPC/s, (iv) Assess the proportion of EPC affect and (v) Calculate final HEP values. The HEP value can be found with following equation (William, 1988).

$$\mathrm{HEP} = \mathrm{GEP}_{\mathrm{value}} \times [(W_i - 1) \times \mathrm{APOA}_1 + 1] \times [(W_j - 1) \times \mathrm{APOA}_2 + 1] \times \ldots \quad (1)$$

where $W_i$ and $W_j$ indicate weight for each context task chosen from EPC tables. The APOA (assess the proportion of affect) states the proportion of the effect which is weighted the each EPC basis of its importance.

### 3.2. AHP methodology

The AHP is a powerful multi-criteria decision making (MCDM) method. It was first introduced by Saaty (1980) in order to provide relative weight of criteria according to hierarchical structure. The method depends on the pair-wise comparison matrix where alternatives are compared respectively. The technique is widely utilised to solve complicated decision problems. The method has been used in numerous disciplines to find out the complex decision problems. The AHP methodology basically divides the complicated problem into small parts in order to rank hierarchically. Thus, relative importance of alternatives will be weighted accordingly. In this article, the AHP method is used to weight/prioritise proportion effect of EPCs.

As the AHP is powerful tool to enable relevant weight for criteria, the first stage is to compose a pair-wise comparison matrix ($A$) as introduced by Saaty (1986). In order to fulfil that Saaty's 1–9 linguistic relative importance scale, provided in Table 1, has been utilised.

The matrix $A$ represents criteria pair-wise comparison matrix where each $a_{ij}$ ($i, j = 1, 2, \ldots, n$) has the relative importance of $i$th elements compared to the $j$th. This indicates that higher value of $a_{ij}$ shows stronger preference of criteria $a_i$ to $a_j$. The matrix is provided in Eq. (2).

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} \quad a_{ii} = 1, a_{ji} = 1/a_{ij}, a_{ij} \neq 0 \quad (2)$$

Thereafter, the priority weights of each criteria will be found with Eq. (3).

$$w_i = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \quad (3)$$

The following step in the AHP method is to prove consistency of data. The reason of this is introduced by Saaty (1986) who proposed a basic equation to control whether the comparison pair-wise matrix is consistent or not. The consistency index (CI) can be calculated by following formula.

$$\mathrm{CI} = \frac{\lambda_{\max.} - n}{n - 1} \quad (4)$$

where

$n$: the order of the matrix

$\lambda_{\max.}$: the maximum matrix eigenvalue

$\lambda_{\max.}$ can be found with Eq. (5) as proposed by Vargas (1982).

$$\sum_{j=1}^{n} \alpha_{ij} w_j = \lambda_{\max} w_i \quad (5)$$

**Table 1**
Saaty's pair-wise comparison scale.

| Importance | Definition |
|---|---|
| 1 | Equal importance |
| 3 | Moderate importance |
| 5 | Strong importance |
| 7 | Very strong importance |
| 9 | Absolute extreme) importance |
| 2, 4, 6, 8 | Intermediate values |

A consistency ratio (CR) calculation is then needed to specify reasonable consistency. The CR value can be calculated by Eq. (6). The CR value will be equal or smaller than 0.10 otherwise the expert judgement will be revised to get consistent result. In the equation, RI stands for random index (RI) and introduced by Saaty (1994). The RI value table is provided in Table 2.

$$CR = CI/RI \tag{6}$$

### 3.3. Integration

In this section, HEART and AHP techniques integration will be introduced to conduct sensitive and consistent HRA for shipboard operations. A flow diagram of proposal approach is illustrated in Fig. 1.

The integration of the proposed approach and main steps are briefly explained as follows.

*Step 1 – Definition of scenario:* The aim of this stage is to define the relevant task in accordance with the scenario which is including main and sub-activities on-board ship. This is performed in line of hierarchical task analysis (HTA) where main steps are divided into sub-steps. Thus, HEP values for each sub-step will give final HEP value for main activities and human reliability can be estimated.

*Step 2 – Nominating generic task:* After defining main and sub-steps based on scenario, relevant generic task type is determine in accordance with the eight qualitative descriptions of actions (A to H) (William, 1988). Then, quantitative GEP value is assigned for each sub-step.

*Step 3 – Identifying relevant EPC/s:* After having determine GEP values as per generic task, relevant EPC/s are selected from the list of 38 possible statements. The EPC is considered to affect human performance negatively therefore increase the GEP value.

*Step 4 – Determining APOA:* In conventional HEART approach. If there are more than one EPC, the experts assign a proportion of the effect which is weighted (prioritised) for each EPC based on its importance. Instead of conducting traditional APOA assessment in HEART, this paper proposes to apply smart solution utilising the AHP technique to weight the importance of each EPC since they are weighted from 0 to 1. So that it improves the accuracy of the calculation during HEP calculation.

*Step 5 – Composing a pair-wise comparison matrix:* If there are more than one EPC, the AHP technique is used. The first step is to establish a pair-wise comparison matrix by using relative importance scale. In this context, Eq. (2) will be applied.

*Step 6 – Calculating criteria weights:* This step provides to prioritise weight of each EPC by using Eq. (3).

*Step 7 – Determining CR values:* To make sure that pair-wise comparison matrix is consistent and reasonable during criteria (EPC) weights, the CR values are found in accordance with Eqs. (4)–(6).

*Step 8 – Calculating HEP value:* In order to find HEP value for each step, Eq. (1) will be applied. Since main task is divided into sub-task in order to find final HEP value, the correlation between the sub-tasks will be revealed by using PSA HTA. Thus, dependency between the main and sub-task HEP value has been provided. The notation can be taken into consideration to calculate the total HEP value of the whole tasks. Table 3 shows the notation in line of the rules to find the total HEP values (He et al., 2008).

- Two sub-tasks are considered as series system in case failure of a sub-task leads to the combination becoming inoperable.
- Two sub-tasks are considered as parallel system in case failure of a sub-task leads to the other part taking over the operations of the failed part.

*Step 9 – Recovery proposal:* In case total HEP value are found higher than desired level (DiMattia et al., 2005), recovery proposal will be recommended in order to reduce probability of human error. In this step, appropriate mitigation measures are taken for EPCs which may cause to increase HEP values accordingly.

*Step 10 – Re-calculating final HEP:*After having proposed recovery actions for EPCs, re-calculation will take a place whether final HEP reduced to acceptable level or not.

**Table 2**
Random index value.

| $n$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

## 4. Demonstration

The proposed hybrid approach is applied to cargo tank cleaning operation on-board chemical tankers in order to perform HRA since it has always potential risk for human life, marine environment and cargo.

### 4.1. Carriage of chemical cargo on-board ship

The carriages of chemical commodities have been increasing strongly in recent years. In order to meet this demand, special types of vessels are designed- chemical tankers which are able to carry numerous different cargoes of different characteristics and inherent hazards. Some of the chemical cargoes are petrochemicals including products of crude oil, natural gas and coal; alcohols and carbohydrates; acids and inorganic chemicals and vegetable, animal oil and fats (IBC Code, 2007). Whilst a variety of different dangerous chemical commodities are transported in the world seas, the following special types of chemical tankers are designed complying with the IBC Code.

- *IMO Type I:* This type of chemical tankers is designed to carry very severe environmental and hazards cargoes such as acid, phenol, phosphorous and phosphate. These types of tankers are required maximum preventive measure since cargoes are very dangerous (IBC Code, 2007).
- *IMO Type II:* This type of ships is designed to transport less severe environmental and hazards cargoes than Type I. For instance, alcohols, benzyl acetate, cyclohexanol, phenol, palm oil, etc. are transported by this type of tankers where significant preventive measure are required (IBC Code, 2007).
- *IMO Type III:* This type of chemical tankers are designed to carry the least dangerous chemical cargoes such as hexanol, ethanol, methyl alcohol, propylene and sulphuric acid where moderate preventive measure are required. (IBC Code, 2007).

As defined above, type I is designed for the greatest hazardous chemical cargoes. Therefore, the cargo tanks of the IMO type I shall be robust to resist the most dangerous cargoes. According to the IBC Code (2007), four types of cargo tanks are designed for chemical tankers. These are independent, integral, gravity and pressure tanks. The most common cargo tank is used on-board chemical tankers is independent type which is able to eliminate stress to ship structure to minimise the risk to the ship. The independent type of cargo tanks can be either stainless steel or coated steel. The stainless steel tanks are the most resistant for aggressive cargoes and acids which are broadly carried by IMO type I chemical

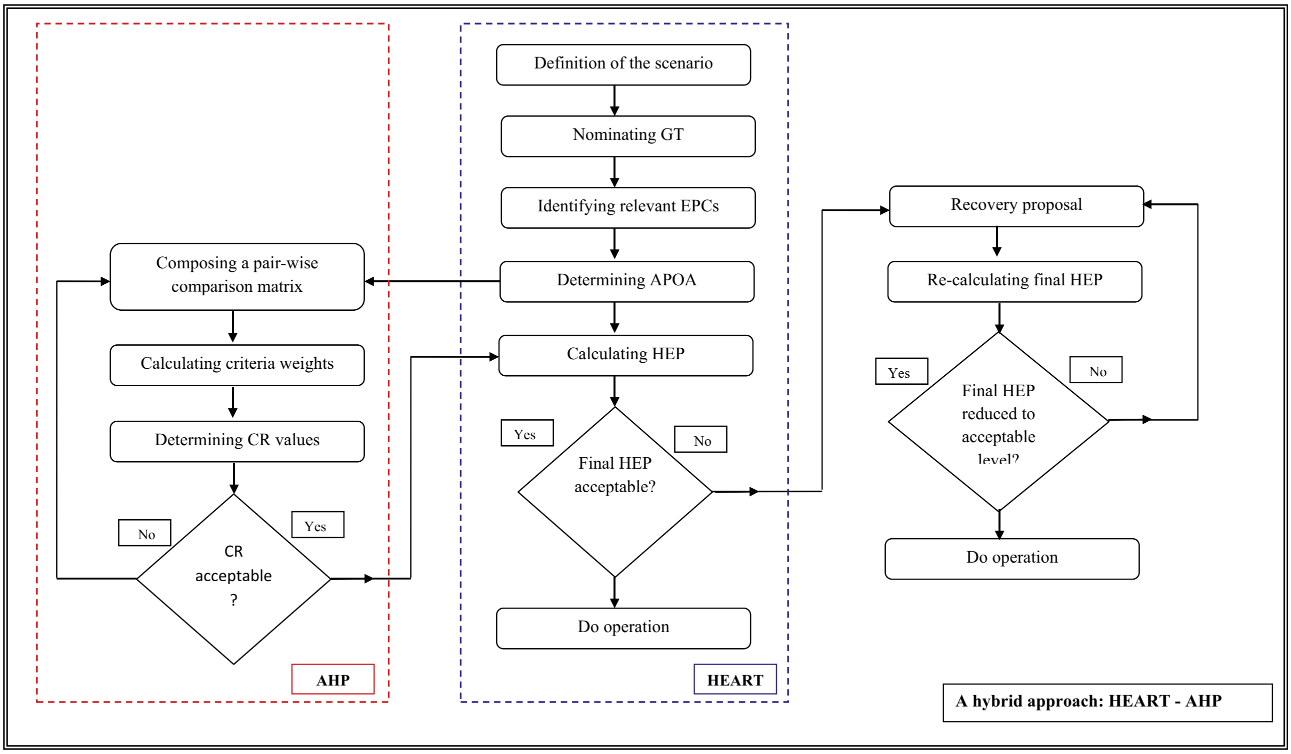


**Fig. 1.** Flow diagram of the proposal approach.

**Table 3**
Equation in line of the rules.

| System description | System sub-task dependency | Notation for task HEP |
|---|---|---|
| Parallel system | High dependency | $HEP_{Task} = Min\{HEP_{Sub\text{-}taski}\}$ |
| | Low or no dependency | $HEP_{Task} = \prod(HEP_{Sub\text{-}taski})$ |
| Serial system | High dependency | $HEP_{Task} = Max\{HEP_{Sub\text{-}taski}\}$ |
| | Low or no dependency | $HEP_{Task} = \sum(HEP_{Sub\text{-}taski})$ |

tankers. The chemical tanker installed with stainless steel provides easier tank cleaning.

### 4.2. Problem description

Chemical tankers carry numerous cargoes, which have different properties and inherits, simultaneously. Due to hazardous inherent of chemicals, the cargo being transported with tankers has potential risks for marine environment and human life. Therefore, well-trained and experienced crew are required especially for cargo tank cleaning process. The vessel is responsible for cleaning of the cargo tanks and cleanliness of tanks depends on the previous cargo contexture. If the previous cargo is hazardous and noxious such as phenol or nitric acid and the next cargo is edible oil and fats such as palm oil or sun flower sea oil; it is imperative that all cargo tanks are cleaned properly. Moreover, gases depending on cargo characteristic release from the cargo tank may induce the hazard. Thus, crew reliability may become a critical consideration during tank cleaning operation whilst it is recognised as potentially dangerous shipboard operation. Therefore, necessary precautionary actions should be taken during each steps of cargo tank cleaning process and crew will be fully aware of the potential hazards to performed duties without any failure. In order to deal with this problem, this paper proposes a model based approach to assess HRA for crew during cargo tank cleaning process in chemical tanker. Thus, continuous monitoring of crew reliability and operational performance should be provided in order to enhance maritime safety.

### 4.3. Cargo tank cleaning operation on-board chemical tanker ship

The cargo tank cleaning operation is known as one of the hazardous operations regularly conducted on-board chemical tankers. Therefore, crew should be aware of the dangers since consequences can be very serious. To demonstrate the proposed approach, the cargo tank cleaning process in chemical tanker is applied into a real-time case study on-board chemical tanker. The cargo is acetic acid which is transported with IMO type-I chemical tankers. The acetic acid is corrosive cargo and can injure human skin. It has severe health and environment hazard. Therefore, it is quite taught and onerous to clean cargo residues after acetic acid cargo discharging operation. If the cargo residues remain tank surface and contaminate the next cargo, it may produces reaction and the consequences can be very dangerous. Marine experts recommended to use liquid water based alkaline chemical agent for this type of cargo during tank cleaning. Table 4 provides the HTA of cargo tank cleaning operation after acetic acid cargo discharging (ICS, 2004).

### 4.4. Definition of scenario

The scenario deals with tank cleaning operation after discharging of acetic acid cargo. The cleaning steps are consisting of eight main steps and thirty sub-steps. The elaborative survey has been carried out with reputed and reliable chemical shipping companies. The fleet has seven IMO types -I and II chemical tankers sailing around the world. The sizes of chemical tankers fleet are ranging from 10,000 to 12,750 dwt. The survey was conducted with marine experts who work in human resource, HSEQ (Health, Safety, Environment & Quality), operation and technical department of companies. The expert profiles include marine

**Table 4**
HTA of tank cleaning process.

| |
|---|
| 1. Prepare to operation |
| 1.1. Get necessary permission from the port authority |
| 1.2. Clean previous cargo residues |
| 1.3. Receive cargo guidance sheet in order to be familiar with hazard |
| 1.4. Prepare safety equipment and personnel protective clothes |
| 1.5. Ensure SOPEP is ready in case any leakage or pollution at sea |
| 1.6. Arrange available slop tank for disposal chemical agent and cleaning water residues |
| 1.7. Check if cargo deck is free from cargo vapour |
| 1.8. Arrange scupper plugs to avoid chemical agent or dirty water leakage overboard |
| 2. Isolate the cargo tanks to be cleaned from the other tanks |
| 2.1. Isolate the cargo tank pipelines |
| 2.2. Isolate the common ventilation system |
| 2.3. Keep close other cargo tanks manholes, tank washing openings and ullage covers |
| 2.4. Keep shut off sea and overboard discharge valves connected to the cargo and ballast systems |
| 3. Check tank washing atmosphere |
| 3.1. Make sure that no source of ignition in an empty tank |
| 3.2. Check if the static electricity is existing |
| 3.3. Ensure that no metallic materials which may induce sparking to be lowered into the tank |
| 3.4. make sure that no steam to be injected into the tanks unless otherwise instructed |
| 4. Arrange tank cleaning equipments |
| 4.1. Arrange portable tank washing machine and hoses |
| 4.2. Incorporate bending wires into the tank hoses |
| 4.3. Secure couplings into the hoses |
| 4.4. Test hoses for electrical continuity in dry condition and make sure that resistance not exceed 6 ohms per metre length |
| 4.5. Check if portable washing machine is supported with natural fibre ropes to avoid electrical continuity |
| 5. Apply heated water into the tank bottom, piping system and discharge line |
| 5.1. Flush heated water into tank bottom, piping system and discharge line |
| 5.2. Strip the water |
| 5.3. Avoid free fall of washing water into slop tank unless tank is inerted |
| 6. Apply special cleaning agent into the cargo tank |
| 6.1. Add special cleaning agent into water |
| 6.2. Detect specific gases or vapours at TLU level inside the tank by using chemical absorption detector |
| 6.3. Permit crew to enter the tank for cleaning (if necessary) if all in order |
| 6.4. Apply chemical agent and fresh water into tank |
| 6.5. Apply chemical solvent to wipe down product residues from the tank wings |
| 6.6. Strip the chemical agent residues and dirty water into slop tank |
| 7. Dispose slop tank into ashore or barge |

superintendents, DPAs, HSEQ managers and ocean going masters who worked for long years on-board chemical tanker ships. The HTA of tank cleaning operation is presented to marine experts and requested to select the most appropriate generic task type for each sub-step. Accordingly, the experts are asked to determine the relevant EPC/s for each sub-step. Since each expert may select different generic task and EPC/s for each sub-step, the consensus of the group is provided in order to get consistent result.

In order to demonstrate the proposed model, the step 3 (check tank washing atmosphere) is described as a sample of process. After acetic acid cargo discharging, tank washing atmosphere takes critical consideration. For instance, it may react with air and induces a hazardous situation. If the tank atmosphere is quite warm (flash point: 43 °C in closed area), the residues of cargo may be flammable. Additionally, metal materials are potential hazard since it may be sparking.

### *4.5. Nominating generic task*

Generic task is defined with the consensus of marine experts. The crew is fairly experienced and has satisfactory skill for tank washing atmosphere. The crew nominated for checking tank washing atmosphere is assured that no source of ignition or any naked flame is placed around the tank. Moreover, they are fully aware of the sparking risk which is caused by metal equipments. They also have enough knowledge that steam injection into tank is very risky. However, the crew member (operator) who is checking the static electricity does not understand the process completely. He has not enough knowledge for this process. In accordance with above clarification, the experts nominate generic task as illustrated in Table 5.

### *4.6. Identifying relevant EPC/s*

The EPC/s are determined by the consensus of marine experts. Since the EPC affects the human performance negatively and raises the GEP value, relevant EPC is chosen from the list of 38 possible statements. Table 5 shows the selected EPC/s for tank washing atmosphere.

### *4.7. Determining APOA*

In order to assess proportion effect of each EPC, the AHP technique is utilised for sensitive calculation. As illustrated in Table 5,

**Table 5**
Generic tasks and EPC/s for tank cleaning process step 3.

| Step | Nominated generic task | GEP value | Selected EPC |
|---|---|---|---|
| 3. Check tank washing atmosphere | | | |
| 3.1. Make sure that no source of ignition in an empty tank | G | 4.00E−04 | EPC#13, EPC#33 |
| 3.2. Check if the static electricity is existing | C | 1.60E−01 | EPC#1, EPC#9, EPC#15, EPC#16, EPC#23 |
| 3.3. Ensure that no metallic materials which may induce sparking to be lowered into the tank | G | 4.00E−04 | EPC#2 |
| 3.4. Make sure that no steam to be injected into the tanks unless otherwise instructed | H | 2.00E−05 | EPC#15, EPC#25, EPC#26 |

**Table 6**
Comparison matrix of EPCs for step 3.2.

| | Unfamiliarity with situation | A need to unlearn a technique | Operator inexperience | An impoverished quality of information | Unreliable instrumentation |
|---|---|---|---|---|---|
| Unfamiliarity with situation | 1 | 4 | 3 | 6 | 3 |
| A need to unlearn a technique | 1/4 | 1 | 1/2 | 1/3 | 1/2 |
| Operator inexperience | 1/3 | 2 | 1 | 3 | 2 |
| An impoverished quality of information | 1/6 | 3 | 1/3 | 1 | 1/3 |
| Unreliable instrumentation | 1/3 | 2 | 1/2 | 3 | 1 |

**Table 7**
Criteria weights for step 3.2.

| EPC | Priority weight |
|---|---|
| Unfamiliarity with situation | 0.453 |
| A need to unlearn a technique | 0.079 |
| Operator inexperience | 0.206 |
| An impoverished quality of information | 0.103 |
| Unreliable instrumentation | 0.158 |

step 3.1, 3.2 and 3.3 have more than one EPC. Therefore, sensitive weighting calculation is needed to calculate HEP value. In this section, step 3.2 is described as a sample.

### 4.8. Composing a pair-wise comparison matrix

A pair-wise comparison matrix is established in accordance with Eq. (2) using a relative importance scale. Whilst group decision is considering in decision process, the experts' opinions have been gathered. They have been asked to describe importance level of each EPC as per Saaty's relative importance scale. Since there are more than one expert (marine superintendents, DPAs, HSEQ managers and ocean going masters), the results of the survey decreased to one comparison matrix by getting geometric means of judgements. Table 6 provides the comparison matrix of selected EPCs for step 3.2 (check if the static electricity is existing).

### 4.9. Calculating criteria weights

The priority weights of each EPC can be calculated in accordance with Eq. (3). Thus, consistent APOA will be provided. Table 7 illustrates the criteria weights for tank cleaning procedure step 3.2 accordingly.

### 4.10. Determining CR values

The CR value can be found with Eqs. (4)–(6). The calculated CR value for step 3.2 is found as 0.087. While the CR value is less than 0.10, the data inserted in pair-wise comparison matrix by experts are found consistent and reasonable.

### 4.11. Calculating HEP value

In accordance with Eq. (1), the HEP value can be calculated for tank washing atmosphere respectively. Table 8 shows the detailed HEP calculation of step 3.

In accordance with the above explanation, the similar HEP calculation is performed for the whole steps. Table 9 shows the entire results.

As the tank cleaning process in chemical tanker consists of 7 main steps and 30 sub-steps in HTA, the final HEP values should be determined in order to assess human reliability. In this context, existing correlation between the main steps and sub-steps in accordance with PSA HTA are utilised. Namely, eight sub-steps shall be conducted properly to complete step 1 (prepare to operation) successfully. This refers a serial system where the step 1 will fail if the any of eight sub-step fails. Therefore, the overall HEP value is found 1.71E−01 since eight sub-steps have a low dependency. Likewise, step 2 (isolate the cargo tanks to be cleaned from the other tanks) will fail in case any of four sub-steps fail (serial system-high dependency). Therefore, the HEP value for step 2 is 5.20E−02. Accordingly, the overall HEP value for step 3 is found 4.29E−01 as there is a high dependency between four sub-steps. Respectively, the overall HEP value is found as 4.82E−03 (parallel system-high dependency) for step 4; 2.86E−01 (serial system-high dependency) for step 5; 2.25E−01 for step 6 (serial system-low dependency) and 8.40E−04 for step 7.

In order to calculate final HEP value for cargo tank cleaning operation on-board chemical tanker, seven main steps should be completed without any error. In this context, if any of these steps fail, the tank cleaning operation will not be performed. Therefore, the final HEP value is 4.29E−01 since there is high dependency between them.

**Table 8**
HEP calculation of step 3.

| Step 3 (tank washing atmosphere) | GEP value | EPC | EPC weight | EPC APOA | HEP value |
|---|---|---|---|---|---|
| 3.1. Make sure that no source of ignition in an empty tank | 4.00E−04 | *A miss match between perceived and real risk<br>*A poor or hostile environment | 13<br>1.15 | 0.678<br>0.321 | 3.83E−03 |
| 3.2. Check if the static electricity is existing | 2.00E−02 | *Unfamiliarity with situation<br>*A need to unlearn a technique<br>*Operator inexperience<br>*An impoverished quality of information<br>*Unreliability instrumentation | 17<br>6<br>3<br>3<br>1.6 | 0.453<br>0.079<br>0.206<br>0.103<br>0.158 | 4.29E−01 |
| 3.3 Ensure that no metallic materials which may induce sparking to be lowered into the tank | 4.00E−04 | *Shortage of time available for error detection | 11 | 1 | 4.40E−03 |
| 3.4 Make sure that no steam to be injected into the tanks unless otherwise instructed | 2.00E−05 | *Operator inexperience<br>*Unclear allocation of function and responsibility<br>*No obvious way to keep track of process | 3<br>1.6<br>1.4 | 0.345<br>0.399<br>0.256 | 4.62E−05 |

**Table 9**
HEP calculation for HTA of tank cleaning process.

| Step | Selected EPC | HEP value |
|---|---|---|
| 1. Prepare to operation | | |
| 1.1. Get necessary permission from the port authority | EPC#15 | 3.40E−03 |
| 1.2. Clean previous cargo residues | EPC#11, EPC#17, EPC#38 | 7.24E−02 |
| 1.3. Receive cargo guidance sheet in order to be familiar with hazard | EPC#2, EPC#13, EPC#18 | 1.45E−02 |
| 1.4. Prepare safety equipment and personnel protective clothes | EPC#2, EPC#23 | 9.50E−02 |
| 1.5. Ensure SOPEP is ready in case any leakage or pollution at sea | EPC#21, EPC#32 | 8.50E−02 |
| 1.6. Arrange available slop tank for disposal chemical agent and cleaning water residues | EPC#10, EPC#25, EPC#33 | 1.01E−01 |
| 1.7. Check if cargo deck is free from cargo vapour | EPC#1, EPC#10, EPC#14, EPC#26 | 1.15E−01 |
| 1.8. Arrange scupper plugs to avoid chemical agent or dirty waterleakage overboard | EPC#19 | 5.20E−03 |
| 2. Isolate the cargo tanks to be cleaned from the other tanks | | |
| 2.1. Isolate the cargo tank pipelines | EPC#3, EPC#14 | 4.60E−02 |
| 2.2. Isolate the common ventilation system | EPC#20, EPC#22, EPC#29 | 1.00E−02 |
| 2.3. Keep close other cargo tanks manholes, tank washing openings and ullage covers | EPC#25, EPC#38 | 8.70E−03 |
| 2.4. Keep shut off sea and overboard discharge valves connected to the cargo and ballast systems | EPC#13, EPC#17 | 5.20E−02 |
| 3. Check tank washing atmosphere | | |
| 3.1. Make sure that no source of ignition in an empty tank | EPC#13, EPC#33 | 3.85E−03 |
| 3.2. Check if the static electricity is existing | EPC#1, EPC#9, EPC#15, EPC#16, EPC#23 | 4.29E−01 |
| 3.3. Ensure that no metallic materials which may induce sparking to be lowered into the tank | EPC#2 | 4.40E−03 |
| 3.4. Make sure that no steam to be injected into the tanks unless otherwise instructed | EPC#15, EPC#25, EPC#26 | 4.62E−05 |
| 4. Arrange tank cleaning equipments | | |
| 4.1. Arrange portable tank washing machine and hoses | EPC#2, EPC#33 | 4.82E−03 |
| 4.2. Incorporate bending wires into the tank hoses | EPC#16, EPC#19, EPC#27 | 3.54E−02 |
| 4.3. Secure couplings into the hoses | EPC#15, EPC#23, EPC#28, EPC#34 | 6.87E−02 |
| 4.4 Test hoses for electrical continuity in dry condition and make sure that resistance not exceed 6 ohms per metre length | EPC#10, EPC#12, EPC#26 | 7.40E−02 |
| 4.5 Check if portable washing machine is supported with natural fibre ropes to avoid electrical continuity | EPC#2, EPC#16, EPC# 19 | 2.19E−02 |
| 5. Apply heated water into the tank bottom, piping system and discharge line | | |
| 5.1. Flush heated water into tank bottom, piping system and discharge line | EPC#10, EPC#33, EPC# 34 | 1.89E−03 |
| 5.2. Strip the water | EPC#34 | 7.50E−04 |
| 5.3. Avoid free fall of washing water into slop tank unless tank is inerted | EPC#1, EPC#15, EPC# 21, EPC#32 | 2.86E−01 |
| 6. Apply special cleaning agent into the cargo tank | | |
| 6.1. Add special cleaning agent into water | EPC#10, EPC#10 | 4.19E−03 |
| 6.2. Detect specific gases or vapours at TLU level inside the tank by using | EPC#13, EPC#13, EPC# 23 | 1.95E−02 |
| 6.3. Permit crew to enter the tank for cleaning (if necessary)if all in order | EPC#21, EPC#31 | 8.52E−04 |
| 6.4. Apply chemical agent and fresh water into tank | EPC#2, EPC#6, EPC# 13, EPC#15 | 1.95E−01 |
| 6.5. Apply chemical solvent to wipe down product residues from the tank wings | EPC#26, EPC#38 | 5.12E−03 |
| 6.6. Strip the chemical residues and dirty water into slop tank | EPC#34 | 1.47E−04 |
| 7. Dispose slop tank into ashore or barge | EPC#19, EPC#28 | 1.41E−02 |

### 4.12. Recovery proposal

The relation between the failure and reliability can be simply defined with $R(t) = 1 - F(t)$ formula. In accordance with the sensitive calculation performed, the reliability value of tank cleaning operation is found as 5.71E−01 which is very low. Therefore, recovery action can be taken in advance to improve performance reliability and decrease HEP value.

Table 10 shows the detail of recovery proposal in order to mitigate the highest HEP values in accordance with DiMattia et al. (2005) risk matrix where the probability of failure combined with the consequence severity. In this matrix, illustrated in Fig. 2, the colour of each block indicates the level of immediate recovery action needed. In the matrix, the HEP value is categorized into four different level of 1.00E+00 to 1.00E−01, 1.00E−01 to 1.00E−02, 1.00E−02 to 1.00E−03, and 1.00E−03 to 1.00E−04 (DiMattia et al., 2005). In this context, the severity of consequences are considered as high level by marine experts since tank cleaning operation in chemical tanker is critical aspect for maritime safety and environment protection. The calculated final HEP value for tank cleaning operation is to be categorized into high risk (red blocks) since the value is found the range of 1.00E+00 to 1.00E−01. To be on a safe side, the final HEP value should be decreased into lower risk level (yellow blocks). Thus, the recovery action is proposed to reduce HEP value into desired level (lower risk level-yellow blocks) by mitigating the EPCs.

### 4.13. Re-calculating HEP value

In the light of above recovery action proposal, the highest HEP values which cause to reduce human reliability can be avoided. In this sense, Eq. (1) is applied. Table 11 illustrates the results of re-calculated HEP values for tank cleaning operation process after mitigation take a place.

The re-calculated HEP values are found after remedial action suggestion for tank cleaning operation. The finding shows that the re-calculated HEP values are 8.45E−02 for step 1, 5.20E−02 for step 2, 3.20E−02 for step 3, 5.07E−02 for step 4, 3.6E−03 for step 5, 2.10E−02 for step 6 and 1.41E−02 for step 7 respectively. Since the system has high dependency, the final re-calculated HEP value is found 8.45E−02. Thus, it is reduced to lower risk (yellow blocks) and categorized in the range of 1.00E−01 to 1.00E−02 in accordance with risk matrix provided in Fig. 2.

## 5. Discussion

Since scarcity of data leading to uncertainty for the majority HRA methods, this paper provides a methodological extension through integrating the AHP technique into HEART approach. Thus, a hybrid approach improves the overall accuracy on which the consistency of proportion affect in HEP calculation is increased. Furthermore, dependency is provided as practice of the reliability estimation with the serial or parallel systems to calculate final HEP. The modification along with the suggested hybrid model is

**Table 10**
Recovery proposal to mitigate the relevant EPC.

| Step | EPC | Remedial action |
|---|---|---|
| 1.7 | EPC#1 | ⁎Apply theoretical and practical familiarization training to crew in respect to cargo vapour hazards before they embark the ship<br>⁎Raise awareness about the potential danger of cargo vapour on deck |
| | EPC#10 | ⁎Increase safety meeting frequency to be held on-board ship in order to transfer of specific knowledge task by face to face<br>⁎Provide effective communication between the crew to establish proper knowledge transfer |
| | EPC#14 | ⁎Post illustrated instructions on appropriate place to assist operator/crew<br>⁎Maintenance proper checklist to provide guidance for operator |
| 3.2 | EPC#1 | ⁎Provide a safety checklist to guide the operator directly<br>⁎Carry out visual practical training for crew to fully understand static electricity checking procedures |
| | EPC#9 | ⁎Apply pre-work procedures to enhance awareness and willingness into task<br>⁎Request operator/crew to complete training successfully |
| | EPC#15 | ⁎Nominate experienced crew to teach how to do task and give necessary support<br>⁎Apply theoretical and practical training concerning how to conduct static electricity testing |
| | EPC#16 | ⁎Establish effective communication between the crew<br>⁎Create written documents for specific tasks in accordance with ISM Code to increase quality of information |
| 5.3 | EPC#1 | ⁎Stipulate to complete necessary training programme before embarking ship<br>⁎Enhance situation awareness by showing visual practice |
| | EPC#15 | ⁎Not assign inexperienced crew alone since the task includes high risk<br>⁎Support inexperienced crew by the expert crew and apply practical training accordingly |
| | EPC#21 | ⁎Conduct safety meeting regularly and explain to crew clearly why this task is so dangerous<br>⁎Provide clear guidance crew not to apply any procedures other than instructed for this operation |
| 6.4 | EPC#2 | ⁎Nominate experienced crew to perform task timely<br>⁎Post illustrated instruction to be followed by crew to save the time |
| | EPC#6 | ⁎Perform necessary training on-board ship to prevent mismatch<br>⁎Provide illustrated guidance for crew to enhance knowledge about chemical agents |
| | EPC#13 | ⁎Perform training programme for crew before they embark the ship in order to enhance awareness about the chemical agent application which is quite risky task than their perception<br>⁎Ensure safety meeting to be held on-board ship to fully understand the operating procedures |
| | EPC#15 | ⁎Ensure crew/inexperienced operator complete the training successfully for this job<br>⁎Not assign inexperienced crew alone since the task includes high risk |

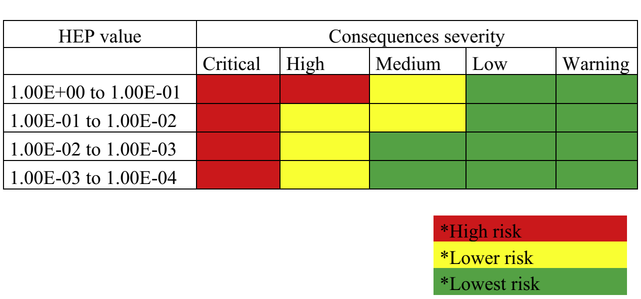


**Fig. 2.** Risk matrix.

**Table 11**
Re-calculated HEP values.

| Step | | Selected EPC | Re-calculated HEP value |
|---|---|---|---|
| 1. | | | |
| | 1.1 | EPC#15 | 3.40E−03 |
| | 1.2 | EPC#11, EPC#17, EPC#38 | 7.23E−03 |
| | 1.3 | EPC#2, EPC#13, EPC#18 | 1.45E−02 |
| | 1.4 | EPC#2, EPC#23 | 9.50E−03 |
| | 1.5 | EPC#21, EPC#32 | 6.50E−03 |
| | 1.6 | EPC#10, EPC#25, EPC#33 | 1.01E−02 |
| | 1.7 | EPC#26 | 2.80E−02 |
| | 1.8 | EPC#19 | 5.20E−03 |
| 2. | | | |
| | 2.1 | EPC#3, EPC#14 | 4.60E−02 |
| | 2.2 | EPC#20, EPC#22, EPC#29 | 1.00E−02 |
| | 2.3 | EPC#25, EPC#38 | 8.70E−03 |
| | 2.4 | EPC#13, EPC#17 | 5.20E−02 |
| 3. | | | |
| | 3.1 | EPC#13, EPC#33 | 3.85E−03 |
| | 3.2 | EPC#23 | 3.20E−02 |
| | 3.3 | EPC#2 | 4.40E−03 |
| | 3.4 | EPC#15, EPC#25, EPC#26 | 4.62E−05 |
| 4. | | | |
| | 4.1 | EPC#2, EPC#33 | 4.82E−03 |
| | 4.2 | EPC#16, EPC#19, EPC#27 | 3.54E−02 |
| | 4.3 | EPC#15, EPC#23, EPC#28, EPC#34 | 5.07E−02 |
| | 4.4 | EPC#10, EPC#12, EPC#26 | 3.40E−02 |
| | 4.5 | EPC#2, EPC#16, EPC# 19 | 2.19E−02 |
| 5. | | | |
| | 5.1 | EPC#10, EPC#33, EPC# 34 | 1.89E−03 |
| | 5.2 | EPC#34 | 7.50E−04 |
| | 5.3 | EPC#32 | 3.60E−03 |
| 6. | | | |
| | 6.1 | EPC#10, EPC#10 | 4.19E−03 |
| | 6.2 | EPC#13, EPC#13, EPC# 23 | 1.95E−02 |
| | 6.3 | EPC#21, EPC#31 | 8.52E−04 |
| | 6.4 | EPC#35 | 2.10E−02 |
| | 6.5 | EPC#26, EPC#38 | 5.12E−03 |
| | 6.6 | EPC#34 | 1.47E−04 |
| 7. | | EPC#19, EPC#28 | 1.41E−02 |

demonstrated with cargo tank cleaning operation which has relatively higher critically compared to other operations on-board chemical tanker ship.

This paper developed an approach which utilizes HEART to calculate HEP values for each sub-step of cargo tank cleaning process whilst the AHP methodology is used to prioritise the proportion of the effect for the selected EPCs. Thereafter, the HEP values of each step are calculated by utilising PSA HTA. The finding shows that operator error probability in this operation is very high (4.29E−01) and categorized into high risk level. Apparently, the reason of the high human error probability (i.e. lowest human reliability) is mainly caused by sub-tasks which have the highest HEP value. Particularly, sub-steps 3.2 (check if the static electricity is existing) and 5.3 (avoid free fall of washing water into slop tank unless tank is inerted) have the highest error rates. To mitigate the human error for this tasks, necessary remedial measures should be taken for the EPCs which have the highest proportion affect upon HEP value. After having taken necessary remedial actions, the final HEP value is reduced to 8.45E−02 and categorised into lower risk level. This shows that performance reliability of operator (crew) typically follows planned procedures and it is acceptable level. The demonstration results clearly show that critical tasks within an operation can be completed with higher reliability if operator (crew) decided on suitable remedial actions. Therefore, the performance reliability result is satisfactory and it leads an improvement in the overall levels of safety in tank cleaning operation.

While the definition of scenario in demonstration section is from the point of view marine industry, this framework can be adopted in different field in the industry such as off-shore environment, petrochemical or nuclear industry. The introduced hybrid methodology may also provide a reasonable content to assess and decrease the human error probability for other industries.

## 6. Conclusion

Since the marine accidents are mainly caused by human errors, this article conducts an empirical human reliability analysis for tank cleaning process on-board chemical tanker ship to enhance safety and operational reliability in maritime industry providing a methodological extension through the integration of the AHP into the HEART approach. Thus, the ship crew safety performance is improved when the relevant task is performed on-board ship. Besides practical contributions, the paper has theoretical insights. During this research, the followings are highlighted:

(i) Importance of controlling human errors on-board ships
(ii) AHP integration into HEART method
(iii) Reliability-based process improvement
(iv) Enhancement in ship operational safety procedures
(v) Motivation towards further developments in HRA

In conclusion, this research conceptualizes and demonstrates HEART-AHP approach illustrated with a case study on tank cleaning operation on-board chemical tanker ship. Although HEART is preferred as safety solution tool in different industries such as nuclear and petrochemical, numeric values of GT and EPC are required to modify in order to comply with the other industries. Indeed, calculating the revised GTs and EPCs values specific to maritime industry in terms of ship operating environment is considered within further research plan.

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