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Risk Analysis Study for Wall Washing Test Applied to Chemical Cargo Tanks

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ABSTRACT

High sensitivity must be shown during the transportation of chemical cargoes due to their flammability, toxicity, purity and incompatibility with each other. Therefore, one of the most crucial procedures in chemical tankers is cleaning the tanks of cargo residues and getting them ready for loading the cargo. Inspection of the tank's suitability for the loading is first performed by a wall wash test (WWT). Evaluation of the errors made during WWT application is essential to prevent cargo contamination with costly consequences. In this study, the risks associated with the application of WWT are analyzed using the Bayes technique in a fuzzy environment. The Bayesian network is used to detect hazards and calculate the probabilities of contributing sub-causes, while fuzzy logic is utilized to quantify the uncertainty in risk assessment. The paper provides practical contributions to all maritime stakeholders in assessing and preventing risks in WWT to the contamination problem, which is one of the most critical problems of chemical tanker transport.

Keywords: Wall washing test, Chemical tanker, Fuzzy Bayesian networks, Contamination

Kimyasal Kargo Tankına Uygulanan Duvar Yıkama Testine İlişkin Risk Analizi Çalışması

ÖZ

Kimyasal yüklerin taşınması sırasında yanıcılığı, toksisitesi, saflığı ve birbiriyle uyumsuzluğu nedeniyle yüksek hassasiyet gösterilmesi gerekmektedir. Bu nedenle kimyasal tankerlerde en önemli işlemlerden biri tankların yük kalıntılarından temizlenmesi ve yük yüklemeye hazır hale getirilmesidir. Tankın yüklemeye uygunluğunun kontrolü öncelikle duvar yıkama testi (WWT) ile gerçekleştirilir. WWT uygulaması sırasında yapılan hataların değerlendirilmesi, maliyetli sonuçlar doğurabilecek kargo kontaminasyonunun önlenmesi açısından önemlidir. Bu çalışmada, WWT'nin uygulanmasıyla ilişkili riskler bulanık ortamda Bayes tekniği kullanılarak analiz edilmiştir. Bayes ağı, tehlikeleri tespit etmek ve katkıda bulunan alt nedenlerin olasılıklarını hesaplamak için kullanılırken, risk değerlendirmesindeki belirsizliği ölçmek için bulanık mantık kullanılır. Makale, kimyasal tanker taşımacılığının en kritik sorunlarından biri olan kontaminasyon sorununa yönelik WWT'deki risklerin değerlendirilmesi ve önlenmesi konusunda tüm denizcilik paydaşlarına pratik katkılar sunmaktadır.

Anahtar Kelimeler: Duvar yıkama testi, Kimyasak tanker, Bulanık Bayes ağları, Bulaşma

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1. Introduction

Maritime transport significantly contributes to world trade due to its capacity to transport large volumes, facilitating transactions over long distances between countries and being more economical than other modes of transport (air, road and rail transport) in terms of transport costs per tonne. (Bai et al., 2021; Uğurlu et al., 2016). Therefore, it is the most preferred mode of transportation. On the other hand, specialized vessels are needed to provide suitable transport conditions for different types of cargo (packaged, wheeled, bulk, liquid, etc.). In the post-World War II period, chemical cargo transport gained importance with the growth of the chemical industry. (Mohammed and Williamson, 2004). Today, chemical tankers carry more than 50,000 different chemicals, including acids, alkaline, alcohol, monomers, chlorinated alkenes and other chemicals. Many of these cargoes have hazardous and/or harmful properties to human health and/or the environment, such as flammability, toxicity, corrosiveness, and oxidizing effects (IMO, 2020). For this reason, cargoes must be carefully evaluated and monitored from planning to discharge.

One of the operations on chemical tankers is tank cleaning. Due to the variety of chemicals, storing consecutively compatible or identical cargoes in the same tank is rare. Most of the chemicals transported are prone to mix or react with impurities or cleaning agent residues from previous cargoes remaining on the floor or bulkheads of the tanks. It is, therefore, critical to eliminate the risk of mixing contaminant, reactive and potentially incompatible cargoes. Mixing incompatible cargoes can result in exothermic, toxic and even explosive reactions. Aside from the potential safety implications, residues of previous cargo, even in minimal quantities, may lead to contamination and consequential financial losses (Senol and Yasli, 2021; Wu et al., 2023).

The Swedish club, which insures 2375 vessels totaling 92 million gross tonnage as of 2022, stated in its analysis report on protection and indemnity (P&I) claims statistics for chemical tankers between 2016 and 2020 that cargo claims are the most common and costly, with 10% of all insured tankers suffering a cargo claim per year. In the same report, the most common types of cargo claims were listed as contamination (39%), Shortage (33%) and Off-spec (24%). Among the known causes of cargo claims, insufficient cleaning has a rate of 21% URL-1 (2023).

The tank washing process depends on many factors, such as the chemical and physical properties of the previous cargo, the type of tank coating, the size and shape of the tanks and the requirements for cleaning the cargo. In addition to following the specified steps during cleaning, it is also essential to continuously monitor the process and check the effectiveness of each stage. Before the cargo is loaded, a wall wash test is performed to determine whether the cleanliness of the tanks is satisfactory. Thanks to the accuracy of the WWT, cargo contamination incidents and costs can be reduced. In this context, the chemical transport industry has developed solutions/procedures over time to ensure the suitability of the WWT (INTERTANKO, 2017). The methods applied during the WWT are based on practical experience. Therefore, conducting studies to evaluate the root causes, risks and consequences of problems during the implementation of the WWT will provide significant savings for all parties of chemical cargo transport.

This study analyses the errors made during the wall wash test using the Bayesian network method, a numerical method based on expert opinion in a fuzzy set environment. The following is the breakdown of the article. The article's goal and the literature review are both included in this part. The article's approach is described in Section 2. To illustrate the use of the suggested method, Section 3 provides a thorough quantitative and qualitative risk analysis of the WWT application. The last section concludes the paper with possible recommendations and suggestions for future work.

2. Literature Review

There are many studies on chemical tanker operations in the literature. In general, studies on sampling (Sezer et al., 2023a) discharge of washing water into the sea (Şanlıer, 2018), loading operation (Ay et al., 2022), fire and explosion accident (Elidolu et al., 2022; Uğurlu, 2016) organizational and individual safety factors (Hjellvik et al., 2019) environmental pollution (Aydin et al., 2021) port operations (Khan et al., 2022) on subjects as different as.

Considering the operations of chemical tankers, the importance of tank cleaning, sectoral and academic studies have made significant contributions to the industry. Some of the studies on tank cleaning are as follows. Wu et al. (2023) summarized research on tank-washing operations in chemical tankers. They defined the primary process and standards of the cleaning process. Then, they analyzed the main factors affecting cleaning. As a result of their study highlighted the lack of quantitative research on gas and oxygen concentration distribution in cargo tanks, optimization of tank washing procedures and tank machine washing parameters for safe and efficient tank cleaning operations. Sezer et al. (2023b) proposed prediction modelling of human error during tank washing operations in chemical tankers. They used the Success Likelihood Index Method (SLIM) and Evidential Reasoning (ER) models together in this context. As a result of the study, they listed the most critical tasks as the use of cleaning agents added to the water according to the cleaning manual, monitoring the Lower Flammability Limit (LFL) during washing and proper collection or discharge of residual water mixture during cleaning according to the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex II standards. In the study where the risks in another tank cleaning operation were evaluated, a comprehensive risk assessment was carried out to increase the effectiveness of tank cleaning operations. In this context, they used the fuzzy Bayesian networks model to identify the factors and causal relationships that cause contaminated tanks. They listed the most essential reasons affecting the tank concentration as the seafarer's lack of technical knowledge and situational awareness. To reduce the risk of contamination, they recommended implementing a continuous training and evaluation program for the ship personnel participating in the tank cleaning operation. (Senol and Yasli, 2021). Akyuz and Celik (2015) calculated the human reliability during tank cleaning operations on chemical tankers by using HEART and AHP methods. They stated that the subtasks with the lowest human reliability check for static electricity and avoid the free fall of slop tank wash water unless the tank is inert. As a result of their study, they claimed that critical tasks in operations can be completed with higher safety if the ship personnel plan appropriate corrective actions. Şakar and Zorba (2017) examined the probabilistic relationship between the causes of fire and explosion accidents that may occur in tank washing operations in oil and chemical tankers with a fuzzy Bayesian networks model. As a result of their study, they stated that the most important causes of fire and explosion in the tank cleaning process are ignition sources, reaction and safety culture. Finally, Senol et al. (2015) calculated the root causes and risk of chemical cargo contamination using the fuzzy fault tree method. They stated that inappropriate operation is the most important root cause of cargo contamination. As it is understood from the above literature introduction, there is no academic research on the analysis of errors made during the wall wash test, which is the control phase of tank cleaning on chemical tankers.

3. Methodology

The theoretical background of the suggested method for assessing errors produced during WWT is presented in this chapter.

3.1. Bayesian Networks

Bayesian Networks or Bayesian Belief Networks are directed acyclic diagrams consisting of nodes denoting variables with a finite number of states and arrows denoting conditional probability dependencies between these variables. The nodes to which arrows are directed are called "child nodes", the nodes to which arrows are directed are called "parent nodes", and the nodes to which no arrows are directed are called "root nodes". The "child" nodes from which no arrows are sent are called "Leaf Nodes" (Bayes Fusion 2017). Bayesian Networks describe the causal relationships within a set of variables of interest, their conditional independence assumptions and their associated composite probabilities. These causal relationships between variables, or in other words, between nodes, are represented by a Directed Acyclic Graph, which identifies both correlated nodes and uncorrelated nodes (Bartlett and Cussens, 2017).

A Bayesian Network consists of two parts: quantitative and qualitative. The qualitative side of a Bayesian Network, also called structure learning, consists of a structure in the form of a directed loop-free diagram in which the independencies between variables are graphically represented. The quantitative side of a Bayesian Network, also called Parameter Learning, is a structure that establishes dependency relationships between variables in the form of composite probability distributions by using the connections on the qualitative side and the data of the variables.

Bayes' theorem conditional probabilities calculations are formulated as Equation (1) (Fenton and Neil, 2013).

$$P(A/B) = \frac{P(A \cap B)}{P(B)} = \frac{P(B).P(B/A)}{P(B)} \tag{1}$$

3.2. Fuzzy

In 1965, Lotfi A. Zadeh wrote an article titled "The Theory of Fuzzy Logic and Fuzzy Sets" as the first formal introduction to fuzzy logic (Zadeh, 1965). However, it wasn't until the 1970s that it was used more regularly. When the Japanese started applying fuzzy logic ideas to manufacturing in the 1980s, it significantly increased in popularity.

Fuzzy logic is a mathematical approach for processing uncertain and imprecise information. While traditional logic is based on the assumption that a statement is either true (1) or false (0), fuzzy logic softens this sharp distinction and recognizes the concept of "partial truth". It defines a membership function that gives each object a membership degree between 0 and 1. Here, the numbers 0 and 1 represent the degree of membership or partial membership of the item to the set. The number 0 shows that the object is not a set member, while the number 1 represents the object as a full member.

If A is an element of the set $R \in (-\infty, +\infty)$, the membership function $\mu A(x)$ occurs in the interval $R \rightarrow [0, 1]$. In other words, if the set A is in the interval $A = [a1, a3]$ in general, the membership function $\mu A(x)$ can be represented by Equation (2).

$$\mu_{\tilde{A}}(x = \begin{Bmatrix} 0, & x < a_1 \\ 1, & a_2 \leq x \leq a_3 \\ 0, & x > a_3 \end{Bmatrix} \tag{2}$$

Membership functions are generally analyzed under two headings: triangular membership functions and trapezoidal membership functions. In this study, triangular membership functions are used. The triangular membership function $\mu A(x)$ is defined in Equation (3) (Kosko, 1994).

$$(x)= \begin{Bmatrix} 0 & ;x \leq a_1 \\ (x-a_1)/(a_2-a_1) & ;a_1 \leq x \leq a_2 \\ (a_3-x)/(a_3-a_2) & ;a_2 \leq x \leq a_3 \\ 0 & ;x \geq a_3 \end{Bmatrix} \tag{3}$$

3.3. Proposed Approach

This chapter demonstrates how to combine the suggested approaches to perform a thorough risk analysis and identify mistakes committed during wall wash testing. Figure 1 depicts the conceptual framework of the proposed strategy. Below is a summary of the approach's steps.

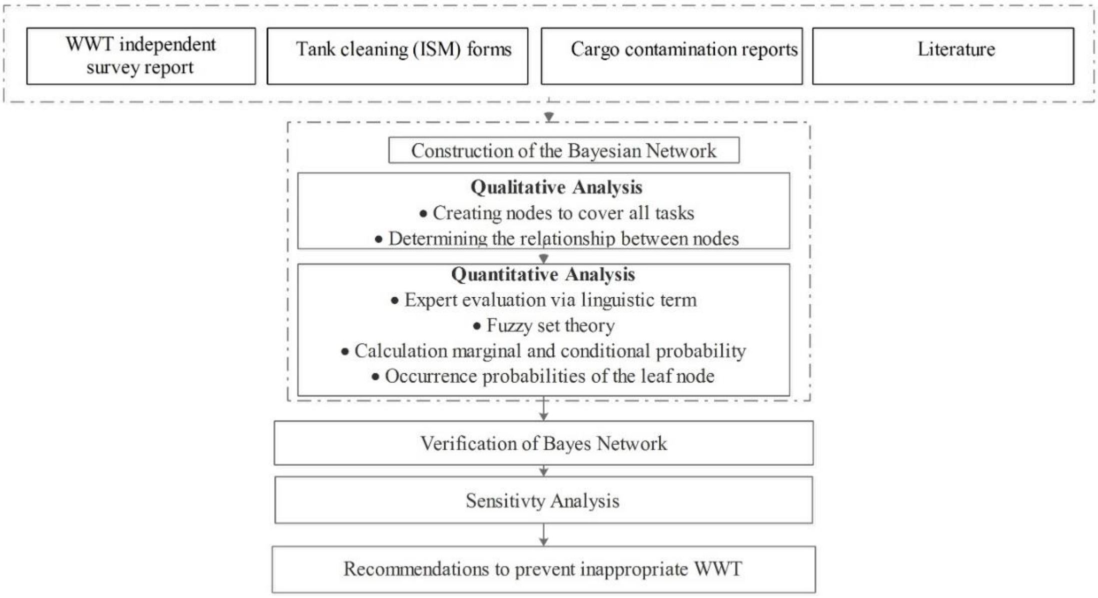

Figure 1. Flow chart of the methodology

Step 1. Bayesian network setup: All information about the event/operation to be analyzed is systematically organized from sources such as literature reviews, industry reports, expert opinions, etc. According to the information obtained, variables (nodes) are created to cover the data. After the variables are determined, the relationship between the variables should be determined. It should be tried to understand which variables depend on others or how they can interact. In this context, creating accimap by analyzing accident or near-miss reports in the literature is a standard variable dependency determination method (Kaptan et al., 2021).

Step 2. Agreement between variable probabilities and expert opinion: The node probabilities assigned in the network structure affect the ability of a Bayesian network to produce meaningful findings. Three primary methodologies have been used in the literature when determining the possibilities of the nodes in the Bayesian network structure in this context. These include statistical information, professional opinion, and the incorporation of both in the computations (Matellini et al., 2013). Conditional probabilities are calculated using expert judgment if insufficient statistical evidence is available for the occurrence under examination. Due to insufficient statistical data for computing conditional probabilities, this study conducted analyses based on expert judgment.

There may not be a homogeneous set of experts whose opinions are sought for the study. This circumstance brings forth divergent expert perspectives. In the formation of this situation, differences in work experience, experience, position, education, etc. can be counted as the cause. Researchers determine the relative quality of expert opinions by using a weight factor. A score between 1 and 5 is given to indicate the differences of each expert. The weight scores of the experts were determined using Equation (4).

$$Weighting\ factor\ of\ expert\ (W_{\mu}) = \frac{Weighting\ score\ of\ the\ expert}{In\ all\ weight\ score\ of\ experts} \quad (4)$$

The membership function defines fuzzy numbers and gives each expert judgment a membership degree between 0 and 1. Any numeral in this range denotes the degree of full or partial membership of the pertinent expert judgment to the set. Due to its ability to quantify the sensitivity between linguistic variables, security researchers frequently use trapezoidal and triangular fuzzy numbers. The study makes use of triangular membership functions. Furthermore, a linguistic scale of seven phrases was chosen to professionally appraise nodes with unknown conditional probabilities. From the lowest rates to the greatest rates, the mistake probability of the fundamental occurrences is scaled.

It is crucial to compile the information discovered through professional examination and to agree on the various viewpoints. As a result, "m" quantity of quantitative data (opinions) from "M" number of experts are integrated for each significant occurrence. The strategy advocated by (Hsu and Chen, 1996), which entails gathering various language responses and putting them into a format appropriate for the fuzzy logic method, was used in this study. The presumption is that. E_U (u= 1 to M). E stands for the expert and u for any M expert m. The following is a list of the critical processing steps (Rajakarunakaran et al., 2015)

a- Compute the degree of agreement according to the approach $\tilde{A}_1 = (a_{11}, a_{12}, a_{13})$ and $\tilde{A}_2 = (a_{21}, a_{22}, a_{23})$ form two standard triangular fuzzy number sets. Then, the degree of similarity between these two sets of fuzzy numbers can be obtained by the similarity function of Equation (5).

$$S(\tilde{A}_1, \tilde{A}_2) = 1 - (1/3)\sum_{i=1}^{3} | a_{1i} - a_{2i} | \quad (5)$$

b- In calculating the average agreement (AA-Avarage Agreement) of M experts equation (6);

$$AA(E_u) = \frac{1}{M-1 \sum_{U \neq V, V=1}^{M} S(\tilde{A}_1, \tilde{A}_2)} \quad (6)$$

c- Calculating the degree of RA-Relative Agreement of M experts Equation (7);

$$RA(E_u) \frac{A(E_U)}{\sum_1^M A(E_U)} \quad (7)$$

d- Calculation of the Expert's Consensus Coefficient (CC-Consensus Coefficient) rating Equation (8);

$$CC(E_U) = \beta . w(E_U) + (1 - \beta) . RA(E_U) \quad (8)$$

e- Finally, the aggregated result of expert opinions (aggregated result) $\tilde{R}_{AG}$ value is calculated using Equation 9;

$$\tilde{R}_{AG} = CC(E_1) \times \tilde{R}_1 + CC(E_2) \times \tilde{R}_2 + \ldots + CC(E_M) \times \tilde{R}_M \quad (9)$$

f. Since the values generated up until this point are fuzzy numbers, they require clarification. Among the refinement techniques, the center of area method was used. The following formula applies to the regions cut on the fuzzy output sets: The output values providing the highest membership value are subjected to Equation (10);

$$\text{Defuzzification equation: } X = \frac{\int \mu_i(X)\, dx}{\int \mu_i(X)} \quad (10)$$

For triangular fuzzy number (A ̃)=(a_1,a_2,a_3) Equation (11) is used:

$$X = \frac{\int_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1} x\, dx + \int_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2} x\, dx}{\int_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1} dx + \int_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2} dx} = \frac{1}{3}(a_1 + a_2 + a_3) \quad (11)$$

Step 3. Validation and sensitivity analysis of the Bayesian network: The Bayesian network produced within the scope of the study needs to be validated to test its suitability. In this context, axiom tests are applied to the network. Bayesian network axiom testing is a method used to evaluate and test the reliability of a system or network. Such tests are widely used to determine the reliability of complex and large-scale systems. Bayesian network axiom testing is used to understand how the system reacts to certain actions and how these actions affect the system.

Sensitivity analysis in a Bayesian network is a method used to examine the effect of uncertainties and errors of input variables on outcome predictions. This analysis helps us to understand the uncertainties and errors in how the system may react.

4. Risk Analysis for WWT

4.1. The Wall-Washing Procedure in A Chemical Tanker

WWT is an essential procedure between tank washing and first foot loading. This process is performed in ships at least twice, unofficially and officially. The first one is performed immediately after the ship personnel wash the tank. The ship personnel needs to see the washing result. If the test result is negative, the ship tanks are rewashed. On the other, if the tanks are not suitable as a result of the WWT test performed by the independent survey appointed by the charterer and the carrier, the ship faces situations with severe financial consequences, such as the cancellation of the charter party.

WWT consists of spraying solvent into the tank to detect the residues of the previous size in the tank, collecting the sprayed chemical and analyzing whether the amount of chloride, hydrocarbon, colour particulate matter, etc., in the sample meets the requirements of the cargo carrier. The wall wash test (WWT) can be generally described in 4 steps (INTERTANKO, 2017).

Step 1. Deciding on the tests and solvents to be used in wall wash application: Firstly, the conditions that cause reaction or deterioration of the planned load must be determined. After these conditions are resolved, it is decided which one or which of the following wall wash applications will be performed (Table 1).

Another important aspect is the selection of the best solvent to be used to remove residues from previous loads. In addition, the selected solvent must be compatible with the type of WWT test.

Table 1. Typical tests used in WWT

Test	Method	Assignment Made
Colour Pt/Co ,APHA ,Saybolt	ASTM D- 1209	Residue detection of coloured cargo
Non-volatile substances Nonvolatility Mattermg/100	ASTM D- 1353	Vegetable and animal fats, sediment, dust, rust, residue detection
Miscibility with water	ASTM D-1722	Hydrocarbon residue test
Inorganic chloride ppm	Turbidity, conductivity by titration	Salt and chlorine test
Permanganate time test	ASTM D-1363	Determination of reducing agent
UV transmission/absorbance	Ultraviolet scan spectrophotometer	Aromatics, inhibitors
Sulfuric acid test. Carbonised ones, acid wash test	ASTM E-364 ASTM D-848	
Ph measurement	With Ph paper or device	Acid and caustic residues
Lead	With AAS or XRF instrument	Lead residue in the order of ppb
Smell	ASTM D-1296	Uncharacteristic or residual component odour

* ASTM American Society for Testing and Materials

Step II. Availability of test kit materials: It is defined as preparing test containers and intact chemicals following the decided WWT type.

Step III. In-tank applications: At this stage, firstly, it should be ensured that the gas atmosphere is provided to allow the persons to enter the tank. Then, spraying the determined solvents to certain tank parts and collecting the samples is applied.

Step IV. Out-of-tank applications: Depending on the type of WWT test, the samples are kept or mixed with other chemicals in the desired amount. It is essential to pay attention to chemical reaction times in these processes to ensure that WWT results are accurate and reliable. In addition, all parties should agree on the results' tolerances before authorizing the cargo's loading.

4.2 Bayesian Network Configuration

The identification of the nodes of Bayesian networks and the relationships between them were examined in six different chemical tanker ships in the last five years, wall wash independent survey reports, tank cleaning International Safety Management (ISM) forms, cargo contamination reports and literature. A tentative Bayesian network diagram was constructed by analyzing all conditions and causes of error in the WWT test. After the Bayesian network was created, online interviews were held with the experts via Google Meet and information about their CVs was obtained. Afterwards, they were asked to express their opinions using the linguistic expressions presented in Table 2 to calculate the marginal and conditional probability tables of the nodes.

Table 2. Linguistic expressions and Triangle fuzzy numbers

Linguistic expression	Triangle fuzzy numbers		
	a_1	a_2	a_3
Very low (VL)	0.00	0.04	0.08
Low (L)	0.07	0.13	0.19
Medium low (ML)	0.17	0.27	0.37
Medium (M)	0.35	0.50	0.65
Medium high (MH)	0.63	0.73	0.83
High (H)	0.81	0.87	0.93
Very high (VH)	0.92	0.96	1.00

After taking the opinions of the experts, their opinions were weighted by evaluating their professional positions, WWT different testing experience and sea service time. Table 3 shows the experts' weighting scores. Point values from 0 to 5 were chosen for each expert to reflect differences in evaluation. Table 4 shows data on experts' weighting calculations.

The linguistic expressions obtained from the expert judgment were fuzzified using Equations (5-8) through triangular fuzzy members. Then, they were aggregated using Equation (9) and defuzzification using Equation (10-11).

The marginal probabilities of the root nodes in the Bayesian network obtained from expert evaluation are shown in Table 5.

Table 3. Details and weighting of experts

Constitution	Classification	Score
Professional Position (PP)	Operation manager	5
	Master	4
	Chf. officer	3
	Officer of the watch	2
WWT different testing experience	Greater than 6	5
	6	4
	5	3
	4	2
	3	1
Sea service time	Greater than 20 years	5
	16 to 19	4
	10 to 15	3
	6 to 10	2
	1 to 5	1

Table 4. Weight factors of experts evaluating WWT risks

Expert no.	Professional position	Competency	Weight score Professional position (Score)	WWT different testing experience (Score)	Sea service time (Score)	Total score	Weight factor
1	Operation manager	Oceangoing master	5	5	4	14	0.241
2	Master	Oceangoing master	4	4	5	13	0.224
3	Master	Oceangoing master	4	4	3	11	0.189
4	Chf.officer	Chf.officer	3	3	3	9	0.155
5	Chf.officer	Chf.officer	3	2	2	7	0.120
6	Officer	Officer	2	1	1	4	0.068

Table 5. Linguistic expert evaluation and fuzzy possibility scores (FPS) of the root nodes

Root Notes	States		Expert evaluations for worst states						Aggregation results of root nodes (For worst state)			FPS
	Worst	Best	1	2	3	4	5	6	a_1	a_2	a_3	
Materials to be used in the test	Dirty	Clean	ML	MH	L	ML	ML	M	0.253	0.352	0.451	0.352
Bare hand sampling	Yes	No	L	VL	L	ML	VL	ML	0.074	0.138	0.202	0.138
Condition of the sampled surface	Unsuitable	Suitable	ML	L	L	VL	M	M	0.150	0.238	0.326	0.238
Test control	Bright environment	Dark environment	L	L	ML	ML	ML	L	0.118	0.198	0.277	0.198
Deterioration of chemical	Yes	No	L	ML	ML	ML	VL	VL	0.106	0.182	0.259	0.182
Using unsuitable chemicals while taking the sample	Yes	No	M	L	L	ML	ML	ML	0.167	0.262	0.357	0.262
Position of the sample taken in the tank	Unsuitable	Suitable	L	ML	M	ML	M	L	0.194	0.297	0.400	0.297
Ambient temperature	Not evulated	Evaluated	L	VL	L	ML	M	L	0.108	0.182	0.256	0.182
Chemical usage amount	Unsuitable	Suitable	L	ML	ML	ML	L	ML	0.136	0.222	0.309	0.222
Entering the tank without clean clothes	Yes	No	ML	L	M	VL	ML	M	0.176	0.274	0.371	0.274
Adequate sampling	Unsuitable	Suitable	ML	ML	MH	L	ML	MH	0.280	0.373	0.467	0.373
Color change	Not following	Following	L	VL	ML	L	M	L	0.109	0.184	0.259	0.184
Information on test kit use	Unsufficient	Sufficient	L	L	ML	ML	MH	M	0.206	0.296	0.385	0.296
Response time of chemicals	Not following	Following	ML	MH	L	ML	ML	M	0.140	0.225	0.309	0.225

Bayesian network node probabilities obtained as a result of expert evaluations are shown in Figure 2.

The axiom tests mentioned in different studies were applied to validate the Bayesian network (Kaptan et al., 2021; Pristrom et al., 2016). The network was found to meet the requirements of axiom tests.

4.3. Sensitivity Analysis

Sensitivity analysis enables estimating any network node's impact on modifying other network nodes. The Bayesian network calculates the impact of changes in the inputs (root node, intermediate node) on the outputs (leaf node) (Uğurlu et al., 2020). Genie 3.0 software was used for this calculation (Bayes Fusion, 2017). The probability value of WWT, which is the leaf node of my network, was set to 0% (appropriate), then to 100% (Inappropriate), while the probabilities of other nodes were not changed. The change in the probability values of the nodes was analyzed. Thus, the effects of the reasons (nodes) that cause the WWT test to be inappropriate on the accident occurrence were quantitatively calculated utilizing the Bayesian network created in the study. Table 6 shows the results of the sensitivity analysis.

Table 6. Sensitivity analysis results of the WWT Bayes Network

Factor affecting Inappropriate WWT Node	Probability of Inappropriate WWT (%)		
	0 (%)	**100 (%)**	**Effect(Differences)**
Materials to be used in the test	34	39	5
Deterioration of chemical	14	43	29
Chemical usage amount	22	25	3
Information on test kit use	30	32	2
Using unsuitable chemicals while taking the sample	24	32	8
Entering the tank without clean clothes	26	31	5
Bare hand sampling	14	16	2
Adequate sampling	37	40	3
Position of the sample taken in the tank	29	35	6
Condition of the sampled surface	23	30	7
Response time of chemicals	23	26	3
Ambient temperature	18	20	2
Color change	18	20	2
Test control	20	22	2
Intermediate Node			
Test kit use	20	61	41
Sampling	14	28	14
In-tank test application	27	54	27
Sample area	16	32	16
Out of tank test application	11	22	11

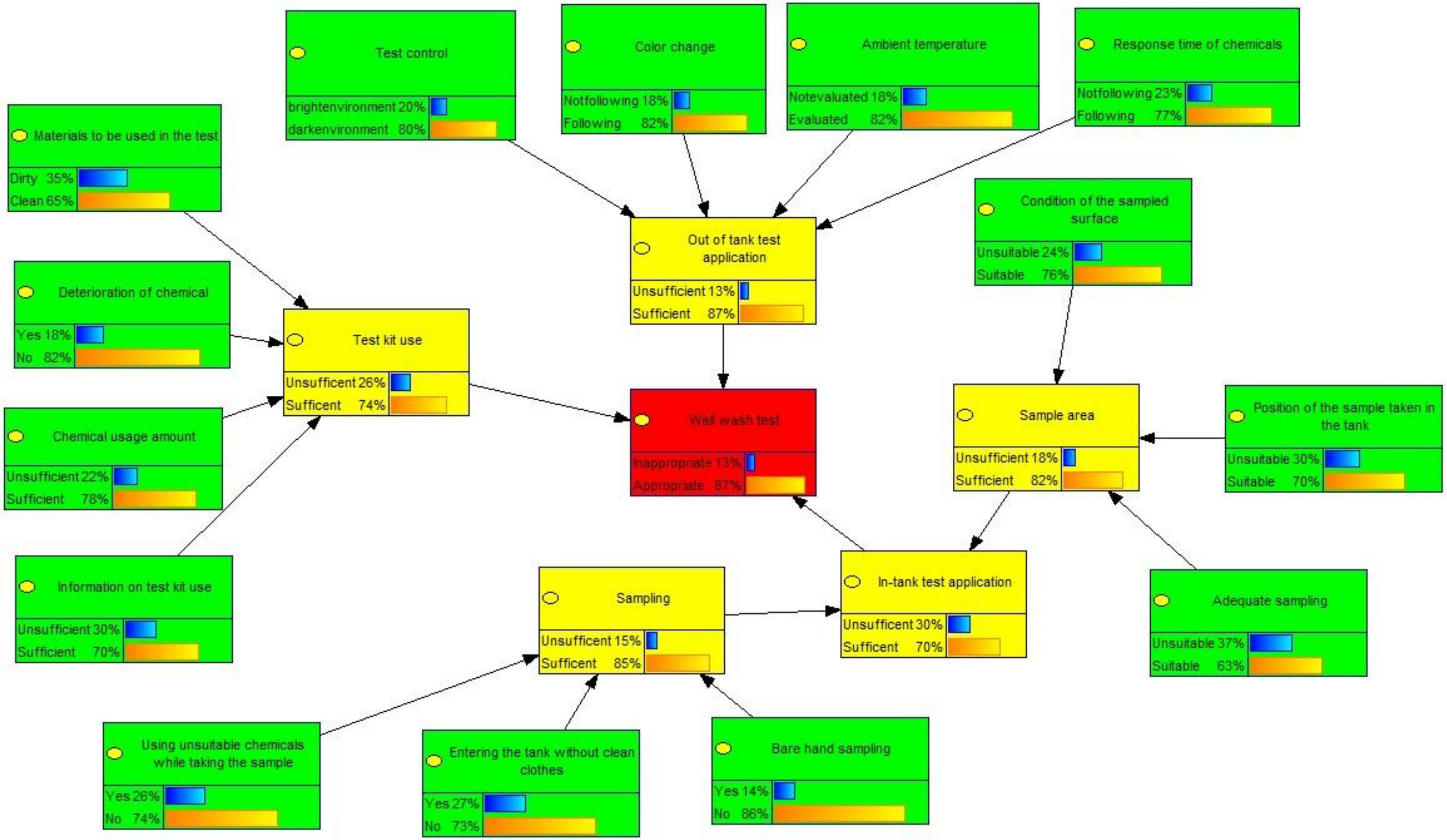

Figure 2. Bayesian network for Inappropriate WWT

5. Results and Discussion

Preventing errors in WWT application depends on understanding the test as a whole. This is possible by identifying all the steps that may cause the test to be inappropriate. The Bayesian network developed for the study's purposes shows the qualitative elements and calculates the quantitative relationships that lead to the WWT application being improper. As a result, network users may comprehend how errors happen in the WWT application and forecast the danger of nonconformity when certain events occur.

The risk probability of the inappropriate WWT test was discovered to be 13% based on the Bayesian network findings attained within the parameters of the investigation. In their study, Senol and Yasli (2021) calculated the probability of nonconformity in the chemical tanker cargo tank cleaning process as 12%. The result was found reasonable when the obtained probability of WWT nonconformity was discussed with the experts participating in the study and compared with the related research.

Considering the findings of the sensitivity analysis‘s effect differences conducted on the obtained network, the root nodes that stand out in the causes of WWT nonconformity are the Deterioration of chemicals (29%), using unsuitable chemicals while taking the sample (8%), the position of the sample taken in the tank (6%) and condition of the sampled surface (7%) (Table 6).

Deterioration of chemical deterioration was found to be the main root cause. WWT in-tank and out-of-tank applications require various chemicals and materials. Common causes of deterioration of these chemicals, expiry date, chemical degradation, contamination, improper storage, physical damage, light sensitivity, moisture exposure, etc. can be listed. In this context, to ensure the reliability of wall washing test results, it is essential to follow the manufacturer's instructions for storage and handling, including paying attention to expiry dates (Brkić et al., 2018). Regular inspection of kit components for signs of deterioration, such as discolouration, texture changes or unusual odours, can also help to identify potential problems (Yao et al., 2023). If any kit materials have deteriorated or expired, they must be replaced to maintain the accuracy and robustness of the testing process.

Besides chemical deterioration, using unsuitable chemicals while taking the sample was identified as another effective node that caused nonconformity of the WWT test. Using unsuitable chemicals while taking the sample during the WWT leads to inaccurate results and safety risks. Unsuitable chemicals can interact with target substances on the surface or interfere with analytical methods, leading to erroneous results. This can lead to false positives or false negatives, which can be problematic when assessing cleanliness or compliance with hygiene standards. On the other hand, there may be safety risks for the persons performing the test and adverse environmental consequences.

The condition of the sampled surface was determined as the other important factor. The structure and material of the hatch surface sampled during the wall wash test affects the sampling process. For example, the material of the tank surface coating (epoxy, polymer coating, etc.) affects sampling and results. (Tekeli et al., 2023). Therefore, to better understand and interpret the test results, it is necessary to consider the hatch's intended use and the surface's characteristics.

The last node that comes to the forefront within the scope of the study is the position of the sample taken in the tank node. The position of the sample taken in the tank during wall wash tests is important because it affects the representativeness of the test results and the accurate assessment of the in-tank cleanliness. Different locations in the tank may have different levels of contamination. Taking the sample from different parts of the tank is vital for representativeness. In addition, the cleaning solution used in wall wash tests interacts with the tank surface and dissolves or mixes contaminants on the surface. Therefore, the area of the tank from which the sample is taken affects factors such as contact time with the solution and its intensity. Sampling for wall wash tests should be carried out carefully to maximize representativeness and assess the in-tank cleanliness status accurately. This is critical to obtain accurate results and assess hygiene or safety compliance (Ay et al., 2022).

6. Conclusion

Cargoes transported in chemical tankers are likely to react with the residues of previously discharged cargoes and deteriorate. Therefore, the tanks must be carefully washed and prepared for the cargo before loading. Since tank washing is a laborious and expensive process, it is essential to be adequately planned, implemented and controlled. Wall washing inspection of tanks after washing determines whether the tank is clean enough to receive the next cargo. It is extremely important to pass the inspection because otherwise, the loading of the next cargo will be delayed, or the loading will be cancelled. In these cases, the ship owner will suffer substantial economic losses. However, it may also happen that the WWT test is passed, but the cargo is spoilt.

Therefore, it is necessary to increase the awareness of the vessel's crew about WWT. Recommendations that will contribute to this are as follows;

- Carefully select chemicals and materials suitable for the specific wall-washing test and target substances.
- Follow established test protocols and standards to ensure consistency and reliability.
- Appropriate training and safety precautions should be provided for personnel working with chemicals.
- Testing materials and equipment should be checked and maintained frequently to ensure they are in good working order.

In the future, it is thought that creating a database under the leadership of the Chemical Distribution Institute (CDI) where WWT test results and cargo status (contamination, deterioration, etc.) can be found and analyzing the data with different methods will significantly contribute to WWT suitability.

Author Contributions

M. Kaptan: Conceptualization, Investigation, Writing – original draft, Software, Formal analysis, Validation, Writing-review & editing.

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