

# Application of Fault Tree - Bayesian Network for Graving Dock Gate

## Failure Analysis

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### ABSTRACT

*Shipyards are complex systems with economic functions; they are subject to specific harsh environmental conditions and are built mainly in areas with increasingly corrosive activity. This chapter focuses on one particular dry dock type called 'relieving graving dock' reinforced with concrete. A detailed quantitative risk analysis with novel fault tree-Bayesian network mapping algorithm is used to rank the most dominant failure mechanisms in terms of risks. The results of this analysis will be a guide for the design, construction and maintenance phase of graving docks applicable to any critical component identified from a risk analysis perspective. The research results should be valuable in enabling industrial participants to manage large engineering risk projects and extending understanding of ship repairing.*

**Key Words:** *Fault tree analysis, Dry dock gate failure, Mapping algorithm.*

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### 1. INTRODUCTION

In recent years, safety analysis has played an important role in the verification of system safety and avoiding casualties and property losses. Actually it is difficult to verify dry dock safety using traditional computer software engineering analysis such as fault tree (FT) ++ given the dependency among the risk factors/events. As an important way for verifying safety in graving dry docks, the fault tree -Bayesian network (FT-BN) has attracted more attention in practice [1].

However, it is still an open question as to how marine safety analysts could make FT-BN more efficient. With the development of science and technology, modern ships have grown in size, while the relationships between upgrading graving docks' equipment and structures of these huge ships have also become more and more complex. The system safety, operational efficiency, life cycle cost control, and maintenance of docking systems have encountered a lot of challenges in terms of practical application [1].

Maintenance actions suggested from hazards identify that more detailed risk analysing techniques are required to avoid catastrophic failure in graving dry docks. Various parties (operators, shipyards, regulators, and government) in their respective working context are very often involved in a sequence of events leading to accidents in graving dry docks, such as the collapse of dry dock gates. This is the most critical issue in graving docks, thus there is a need to develop an effective risk or accident analysis to avoid future operator errors.

For the past decades, risk analysts in dry docks have proposed techniques such as Fault Tree Analysis (FTA), Failure Mode Effects and Critical Analysis (FMECA), and Fuzzy Set Theory (FST). In these methods and technologies, FTA, which generates the use cases by the minimal cut sets of fault trees, cannot determine the priorities of all the use cases and cannot utilise the

finished test results [2]. A more applicable approach to solve this problem is by transferring FT to BN (described in this chapter), expressing the information in FT and BN together. FTA is an important verification methodology for graving dock risk analysis. It is a top down technique used to analyse the origin of the failure, determine the graving dock safety requirements, detect the logic of errors, identify the multiple failure sequence involving different parts of the system (such as human and hardware) [1]. It provides an analytical tool to determine appropriate input data in graving dock analysis. However, traditional FT cannot handle sequential and functional dependencies between components [3]. BN is a directed acyclic graph used to represent uncertain knowledge in the field of graving dock risk analysis. This is defined to consist of qualitative and quantitative relations [4], and because of the advantages of uncertainty and conditional independence expression, the BN provides a comprehensive method of representing variable states and relationships [5]. Also, there exist an efficient method for converting FT to BN easily [6]. In a BN, the nodes represent a random variable; the arcs signify the existence of direct causal influences between variables, and the strengths of these influences are expressed by forward conditional probabilities [7]. Accordingly, this provides BNs with the ability to calculate posterior probabilities of unknown variables in graving dock failure analysis based on the variable evidence and conditional probability distributions.

In this paper, a quantitative approach in the reliability evaluation method of the dry dock failure analysis of a caisson gate of a graving dock has been studied for the application of BN transferred from a fault tree. Section 2 presents the statement of the problem in the graving dock reliability analysis. Section 3 presents a typical steel sliding gate used in this study. Section 4 is a review of FT-BN applications in engineering. Section 5 is an overview of converting a fault tree to its corresponding Bayesian network. Section 6 is the illustrative example of the failure analysis of a dry dock gate highlighting the system reliability. Section 7 provides the discussions and conclusions.

## **2. PROBLEM DEFINITION**

Risk analysis involves two basic types of uncertainty. The first is due to inherent randomness in the phenomenon and the variables chosen to model it. The second is due to inaccurate modelling, and insufficient data [4]. This paper is concerned mainly with the epistemic source of uncertainty, and its propagation through a risk analysis involving rare events such as the collapse of a dry dock gate. In traditional FTA the probabilities of basic events are treated as exact values, which could not reflect the situation of a dry dock gate system because of the ambiguity and imprecision of some basic events. In many circumstances, it is generally difficult to estimate the precise probabilities of basic events. Thus, it is often necessary to develop a new method to capture the imprecision of failure data. In this regard, it may be more appropriate to use BN [6].

Marine works have been subjected more and more to risk analysis over the past few decades; for example, fishing vessels, ports, marine transportation, liner shipping, high-speed crafts, oil tanker, passenger roll on/roll off (roro), vessels with dangerous goods and bulk carriers [8]. Coastal structures like wind turbines [9], optimisation of harbours [10] and harbour monitoring [11] for reliability are other creative areas of risk analysis carried out in marine areas beyond ships and offshore structures. However, the literature review reveals very little on risk analysis on structures used in bringing ships in and out of water for repairs. The graving dock is typical in that it is surrounded by earth on three sides and has a floatable caisson (or gate) at one end. The walls usually consist of two sections: thick walls and/or thin walls [12]. To support fleet operations, it is important to maintain the existing dry docks in a safe condition and to assure that the full capacity of the dry dock is maintained. Each dry dock needs to be initially certified for its safety and capacity for three to five years. To certify the safety of a graving dock, the stability analysis of the dry dock is performed using a finite element analysis. The content of this report is generally based on [12]: A material condition survey performed by a field investigation, structural analysis using a finite element analysis computer program, and the operation and maintenance procedures provided by the shipyard.

The safety certification of a graving dry dock comprises a structural analysis of geotechnical characteristics, structural parameters, soil structural interaction, and load cases. These safety certifications however have not prevented failure happening in graving shipyards. Typical accidents may include collapse of dock walls due to static lateral soil pressure and dynamic earthquake loads. A recent accident involving caisson gate failure on 27 March 2002, at Dubai Dock No 2, one of the world's largest ship repair facilities, caused uncontrolled flooding of the dock leaving 21 people dead [13]. Again, if the dry dock is not founded on deep foundations, such as piles, then a net uplift would result, causing the dry dock to float and tilt. However, according to [12] this failure is not likely to occur.

From a risk analysis perspective, the analyst is required to gather enough data to classify a risk or failure unlikely to occur in a scientific manner. In the preparatory study preceding risk analysis, a detailed study is required to identify critical elements in dry docks. These critical elements are; dry dock gate, walls, piles, concretes, structural components, and ballast system control. These indicators affect the condition diagnosis and ageing diagnosis of components and facilities in dry docks to adapt maintenance

actions for larger fleets. Again, selecting critical elements for risk analysis becomes difficult since most components may be at high risk of collapse due to age. In this study, the risk analysis to support operation and maintenance of an ageing dock gate for the Port of Marseilles authority is re-visited. The dock gate identified as a critical component is further plagued by age. The previous study on a gate failure was based on FMECA with the methodology highlighted as follows [14]: (1) to characterise the risk linked to each foreseen operation scenario; (2) identify the most appropriate actions to control these risks; (3) integrating operation constraints (e.g. the need to put the dock gate in dry dock); (4) rank actions regarding their cost/benefit ratio and; (5) building a maintenance plan.

### 3. DRY DOCK GATES

Dewatering of the dry dock takes place after setting the dock gate, which permits full closing at the highest predicted water level, and opening at least at the mean level. The gate as well as its support must safely withstand the largest water pressure from the water side. Dock gates should fulfil the following objectives [14]: (a) great tightness for all possible loading cases; (b) short opening and closing times; (c) easy servicing and maintenance; (d) mechanical reliability; (e) monitoring of the gate position during opening and closing; and (f) minimum operation and maintenance costs.

Seals should correct any unevenness of the concrete surfaces which could not be eliminated by grinding. Another common problem with the gates is protection against corrosion, ice actions, and they must have sufficient buoyancy to allow them to be placed in their seating and removed for maintenance repair [14]. Again, the dock gate as a whole must be subjected to detailed complex static calculations in order to find the dimension of each structural element and also to establish interaction of the individual sections and the bearing elements. The tightness of the dock depends on these individual elements. Lastly, as water is added to the gate to sink it, the weight of the water causes the centre of gravity to alter as the gate takes on slight angles, raising stability issues [15]. Many types of dock gates are in use nowadays. They are classified as floating, sliding, mitre, hinge, and flap gates but the sliding gate of Dry Dock No. 10 in Marseilles, France is used a case study in this paper with the gates chamber seen in Figure 1. The chamber walls are made as reinforced concrete walls and reinforced concrete angular walls supported on piles. Stability was ensured by installing ground anchors.

This pre-stressed concrete structure has the following dimensions: length 87.35m, width 15m, height 13.5 m as seen in Figure 2, where 1 is the guiding post, 2 is the service road, 3 is the sealing system, and 4 the bearing-panel block. In elevation, the dock gate consists of 28 identical cells, of 5.82m x 6.64m inner size, grouped into four ballast chambers [15].

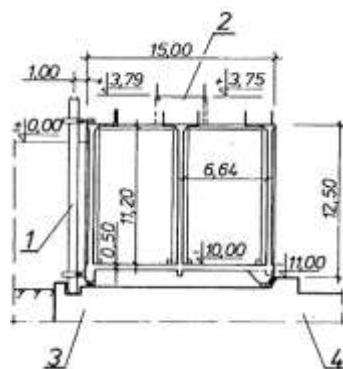


Figure 1: Cross-section of the dock gate [15]

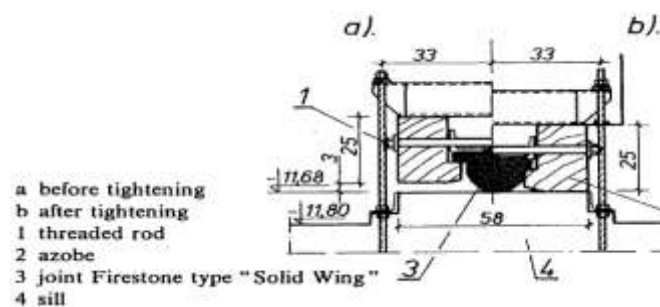


Figure 2: Sealing system [15]

The dock gate is a self-stabilising pre-stressed concrete caisson that behaves like a gravity dam. When closed, the dock gate is supported along two lines: one on the seaward side conveying to the sill vertical reactions that compress the sealing system (Figure 3); the other on the dock side, transmitting the horizontal water pressure components in addition to the vertical reactions to the sill. Due to the sliding nature of these gates, the water pressure is transferred to the dry dock sidewalls and the sill. As a result of gate deformations, the greatest forces are transferred to the sidewalls at the water surface, and to the sill along the axis of the dock. This requires sealing on the side surface of the gate, which also influences the cross-section, which is generally rectangular [15].

To ensure the proper tightness it is advisable, in the light of the above remarks, to construct the sliding tracks so as to permit some side movement of the gate. During the sliding operation the gates are ballasted in such a way that their total reaction on the sliding tracks does not exceed 100 KN. They slide along rails on the dock sill on special wheels fastened to the bottom of the gate, or on rollers. They can also slide on smooth surfaces. In some cases, the gate support is only a wooden or steel beam sliding on the smoothed bed surfaces or on loose rollers in special boxes

### 3 FAULT TREE – BAYESIAN NETWORK

The fault tree – Bayesian network (FT-BN) was applied on the QNX software system with the aim of using BN to express FT, hence allowing the incorporation of both hard and soft evidence into the analysis in a quantifying way [16]. In applying the FT-BN to a neutrino microkernel, a fault tree was developed guided by product history over the period 2002 to 2009. The top event was ‘QNX Neutrino can fail’. FT was mapped to Bayesian network to incorporate soft evidence about field failures rates, and calculate the resulting post-probabilities. Reports of failures in the field with field usage figures to estimate the failure rates were obtained and used in the fault tree. Sensitivity analysis was carried out to find the values to which the final result was most sensitive.

In another study, a comparison was carried out between the FT and BN approach [17]. Though this research took a ‘comparing’ approach, ‘mapping’ was the more efficient term to use. Using fault Tree and Bayesian Network as a failure analysis technique, the applicability of this approach to the performance of ‘a feeding control system transferring propane’ from a propane evaporator to a scrubbing column was tested. All components were assumed binary (work/fail). Six basic events were identified and three intermediate events. Occurrence frequency data of primary events that would contribute to the occurrence of top events were assumed. Considering these probabilities, the prior probability of the top event was calculated as 0.270. ‘Index improvement method’ was used to determine events with a higher index, by keeping some particular event absent. Again, mapping of Fault Tree to Bayesian Network was done to test FT-BN conversion approach. The prior probability was 0.270 using the ‘Hugin Software’. This improvement analysis showed the same results as FTA highlighted.

#### 3.1 Fault Tree Analysis

FTA is a deductive, structured methodology to determine the potential causes of an undesired event, referred to as the top event. The top event usually represents a major accident causing safety hazards or economic loss [18]. Building the fault tree is by a basic procedure, assuming that the top events have occurred and then work backwards to determine the set of possible causes. The necessary preconditions are described at the next level of the tree with either an ‘AND’ or an ‘OR’ relationship.

The immediate events should be considered as sub-top events and the same process should be applied to them until all leaves describe events of calculable probability or are unable to be analysed for some reason. After that, the fault trees are built by the events in the analysis process of this step [2]. A typical example is seen in Figure 3. The system will fail if both failure 3 and failure 2 occur. Failure 2 will occur if either a failure at leaf C or a failure at leaf D (or both) occurs. Failure 3 will occur if either failure 1 or a failure at leaf E (or both) occurs. Failure 1 will occur if both failure at leaf A and a failure at leaf B occur [20].

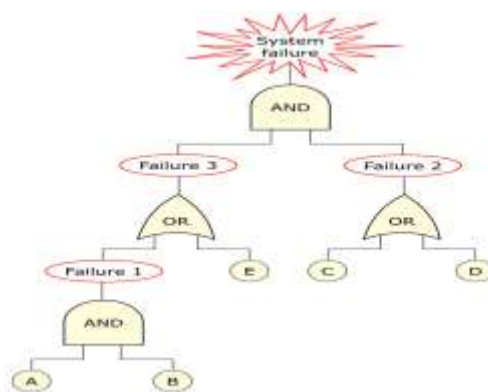


Figure 3: Fault tree of system failure

If a failure follows an exponential distribution, then the likelihood of occurrence of the system failure at time t is expressed in Eq. 1 as follows and the failure rate is presented in Eqn. 2;

$$P(t) = 1 - e^{-\alpha t}, \text{ where } \alpha \text{ is failure rate} \tag{1}$$

$$\text{Failure rate, } \alpha = 1/\text{mean time between failure} \tag{2}$$

Calculating the system failure of the fault tree developed in Figure 4, the Boolean gates are expressed thus:

$$P[S_F] = P(F3, F2), P[F2] = P[C+D], P[F1] = P[A.B] = P[A] + P[B] - P[A.B],$$

if events are independent of each other, where P[X] represents the probability of failure. F1, F2, F3 are failures 1, 2 and 3 respectively, and S<sub>F</sub> is the system failure in Figure 4.

The minimum cut sets is calculated: SF=F3.F2, F2=C+D, F3=F1+E, F1=A.B, F3=A.B+E, S<sub>F</sub>=F3.F2, S<sub>F</sub>= (A.B+E). (C+D)

$$S_F = \underline{ABC+ABD+EC+ED}.$$

Four minimum cut sets expressed can cause the occurrence of the top event, and, by preventing set events from happening, system failure can be avoided. If, for example, the mean time between the failure of events A, B, C, D, and E is 10,000 hours and the system failure is at, t = 5000 hours, failure rate of each events A, B, C, D and E is calculated using Eq. 1 and 2,

Failure rate,  $\alpha$ , = 1/10,000 = 0.0001,  
 $P(A, B, C, D, E) = 1 - e^{-\alpha t} = 1 - e^{-0.0001 \times 5000} = \underline{0.39}$

The value ‘0.39’ follows an exponential distribution and signifies the occurrence probability of the top event. The occurrence probability of top event system failure (S<sub>F</sub>) can be calculated using absorption laws in fault tree quantitative analysis

$$P[S_F] = \frac{P[ABC+ABD+EC+ED]}{U \quad V}$$

$$P[S_F] = P[U + V] = P[U] + P[V] - P[U.V]$$

$$P[S_F] = P[ABC+ABD] + P[EC+ED] - P[(ABC+ABD)(EC+ED)]$$

$$\begin{aligned} P[W+X] &= P[W] + P[X] - P[W.X], \quad P[ABC+ABD] = \\ &P[ABC] + P[ABD] - P[\{ABC\} \{ABD\}] \\ &P[ABC] + P[ABD] - P[ABCD] = \end{aligned}$$

$$0.39 \times 0.39 \times 0.39 + 0.39 \times 0.39 \times 0.39 - [0.39 \times 0.39 \times 0.39 \times 0.39] = 0.095$$

$$\begin{aligned} P[Y+Z] &= P[Y] + P[Z] - P[Y.Z] \\ P[EC+ED] &= P[EC] + P[ED] - P[\{EC\} \{ED\}] \\ &= P[E] P[C] + P[E] P[D] - P[C].P[D]. [E] \\ &= \underline{0.245} \end{aligned}$$

Conversely, if data available shows that the system failed once over a 12-month period, using Eq. 3

$$P = \alpha \times \Omega^{-1} \tag{3}$$

$$1 \text{ failure}/365 \text{ days (1 failure/day)}^{-1} = 0.27\%$$

The value 0.276 means the system fails once in a 12-month period. Where the system fails twice every year, the probability of failure (P) of the top event is 0.54% using equation 3. Using the FT + software available, ‘0.27’ failure rate of the top event is obtained using the same values of basic events’ failure rates. This trivial system is represented in Figure 5; the minimum cut sets can be calculated as {E, C}, {E, D}, {A, B, C}, {A, B, D} but for realistic trees, computer programs are needed to identify minimum cut sets.

### 3.2 Bayesian Network

The Rev. Thomas Bayes published his famous theorem in the 18th century. If belief can be identified with probability, then the theorem allows reasoning from effect to cause as follows:

*if E was true then H would result. H is actually true. This increases my belief in E by a certain amount. Clearly, depending on a priori unlikeliness of E, the amount by which E increases the belief may be very small or quite large.* For example, if two events ‘e’ and ‘h’ are considered where event ‘e’ is the influenced node and event ‘h’ is the influencing node, the Bayes’ theorem P (e) is the prior or marginal probability of e, P (e/h) is the conditional probability of e given h, P (h/e) is the conditional probability of h



given  $e$  and  $P(h)$  is the prior or marginal probability of  $h$ . More formally, given a hypothesis ‘ $h$ ’ and some evidence ‘ $e$ ’, Bayes’ theorem states that [16]:

$$P(h/e) = \frac{P(e/h) P(h)}{P(e/h) P(h) + P(e/\neg h) P(\neg h)} \quad (4)$$

Where  $P(X|Y)$  is the probability that  $X$  occurs given that  $Y$  has occurred and  $\neg X$  means “not  $X$ ”. As a trivial example, assume that: ‘ $h$ ’ is the hypothesis that “It is raining at the moment”. ‘ $e$ ’ is the evidence that “I have just seen Chris with his umbrella”. A node is generally drawn as an oval or circle, representing the variable or event. The arc is generally a straight line with an arrow head illustrating the direction of the link from the source node, often called the ‘parent node’, to the target node, often called the ‘child node’, as in Figure 4, which represents a simple BN consisting of events  $e$ , and  $h$ .

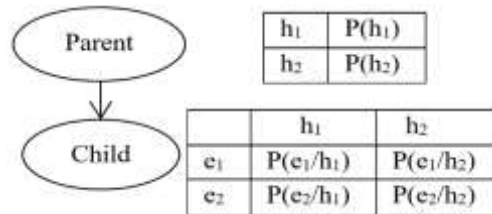


Figure 4: CPT of parent ‘ $h$ ’

The condition probability table (CPT) of parent ‘ $h$ ’ has two states, namely  $h_1$  and  $h_2$ , together with probabilities  $P(h_1)$ ,  $P(h_2)$ . The CPT of event ‘ $e$ ’ has two states,  $e_1$  and  $e_2$ , but the states are influenced by event ‘ $h$ ’. Bayesian networks allow for this difference in failure information by accepting evidence for the failure rate of any node, then using Bayes’ theorem to calculate the ‘*posteriori*’ probabilities of the failure rates of the sub-elements, reasoning from effect to cause. Chris carries his umbrella 60% of the time when it is raining [ $P(e/h) = 0.6$ ]. Chris carries his umbrella 30% of the time when it is not raining [ $P(e/\neg h) = 0.3$ ]. In the area where Chris lives it rains 20% of the time [ $P(h) = 0.20$ ].

This is known in the literature as the ‘*prior*’ probability because it is a measure of the probability of the hypothesis before any evidence is considered. Given these values, a person observing Chris in the street with his umbrella can calculate the probability that it is raining using equation 4 is expressed as:  $(0.6 \times 0.2) / \{(0.6 \times 0.2) + (0.3 \times 0.8)\} = 0.33$ .

This theorem forms the basis of BN modelling. It is therefore a directed acyclic graph that encodes a conditional probability distribution at the nodes of the basis of the arcs received to form an equivalent CPT. From an engineering analysis point of view, given a ‘ship engine’ that requires ‘oil’ for lubrication and ‘water’ for cooling, three nodes can be constructed with engine as child node and coolant pipes and oil pumps as parent nodes. Coolant pipes have two states, either ‘leak’ or ‘no leak’; oil pumps states are ‘fail’ or ‘working’; and engine states are ‘fail’ or ‘running’.

A visual representation of nodes and events that can represent this analysis is presented in Figure 5. Parent nodes are given prior probability and child is given posterior probability. This shows 30% that the coolant pipe will leak and 70% that there is no leak. Similarly, the probability of the oil pump failing or working is 50% from historical failure data, age of the component, and relevant variables. Adopting a chain rule, the nodes, ‘coolant pipe’ and ‘oil pump’ are termed ‘ $Q$ ’ and ‘ $T$ ’ respectively, and the ‘engine’ is termed ‘ $S$ ’.  $S_f$  signifies state ‘engine fails’. The probability of ‘engine failure’ using equation 5 can be calculated as:

$$P(S_f) = \sum_{i=1}^2 \cdot \sum_{j=1}^2 p(C1QT)p(Q_i)p(T_j) \quad (5)$$

Event modelling can also be carried out by using the Hugin software which gives the same results (0.56) as calculated mathematically using Eq. 5.  $P(\text{engine fail}) = P(\text{oil fail}) \times P(\text{coolant leak}) \times P(\text{prior engine fail}) + P(\text{oil fail}) \times P(\text{coolant no leak}) \times P(\text{prior engine fail}) + P(\text{oil work}) \times P(\text{coolant leak}) \times P(\text{prior engine fail}) + P(\text{oil work}) \times P(\text{coolant no leak}) \times P(\text{prior engine fail})$

$$= 0.5 \times 0.3 \times 1 + 0.5 \times 0.7 \times 1 + 0.5 \times 0.3 \times 0.3 + 0.5 \times 0.7 \times 0.05 = \underline{0.56\%}$$

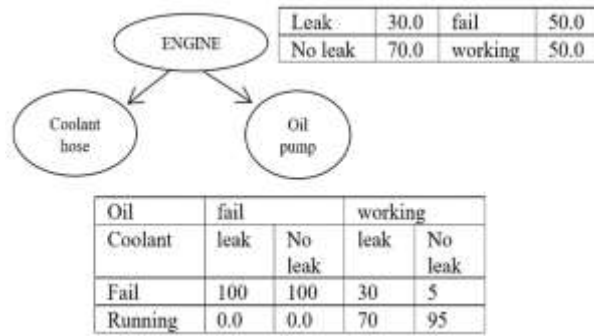


Figure 5: Conditional probability table

### 3.3 Mapping Algorithm

A study on the conversion methodology is appropriate in understanding the building of the BN associated directly with the fault tree as seen in Figure 6. In order to facilitate reasoning, two principles are suggested as a ‘MUST consider’ [19]: (1) the nodes of the BN are associated with the events of fault trees; (2) the distribution of conditional probabilities in the BN is the reflection of the logic gates in the fault tree. In mapping, detailed consideration should be given to the type of Boolean gate used. A simple representation Figure 7 presents the corresponding rule with nodes. With OR gates,  $P_r$  is [0, 1, 1, 1] and  $P_r$  [0, 0, 0, 1] for AND gates where  $P_r$  is probability of parent nodes’ link to child. In reliability evaluation of a mechanical system, it is observed that stated that the BN is directly associated with its FT [20,21]. There further exist difficulties in conversion process of large and complex systems as the conversion analyst needs to redraw the nodes and connect them while correctly enumerating their prior probabilities and conditional probabilities [19]. This task is not easy to accomplish in practice.

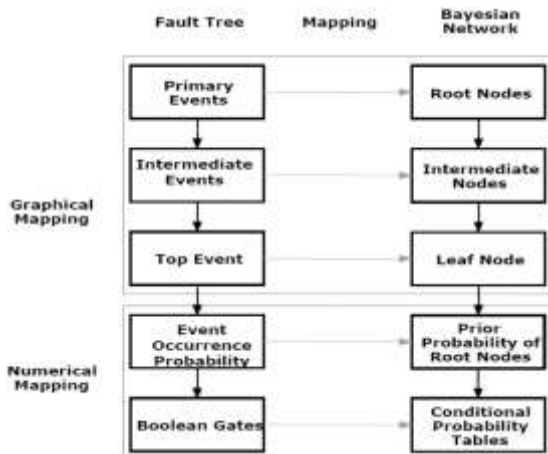


Figure 6: Mapping FT to BN [17]

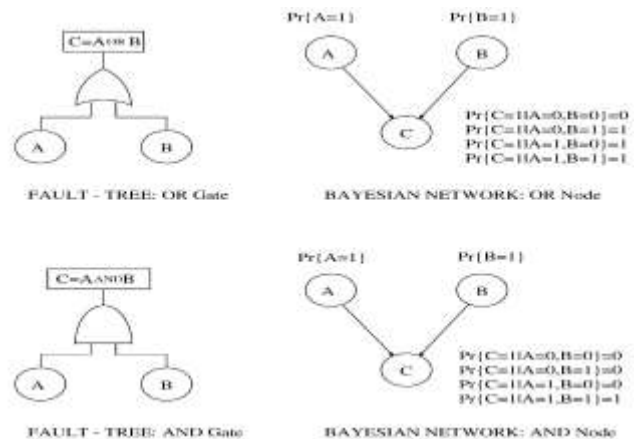


Figure 7: ‘OR’ (top) & ‘AND’(bottom) gate FT-BN [19]

To overcome these difficulties, a detailed work carried out by [21] titled ‘An efficient framework for the conversion of FT to diagnostic BN models’, presented an observation list and fault tree. FT, they said, ‘deal[s] in truth’, whereas diagnostic networks ‘deal in observations of the truth.’ They further highlighted the need of a semantic checking and adjustment in the conversion process [21]. This research was accomplished with the use of Graphical User Interface software with the aid of FT files created in ‘iGrafx’ and BN files in ‘.xds’. It is further claimed that this software, implemented entirely in C++ and running under Windows 2000 and XP, has been tested on a number of real-life FTs, ranging from small size nodes of 20 to 800.

In building a BN from FT, first the FT is used to create the structure and parameters of the BN, then observation nodes from the observation list, which augments the domain knowledge contained in FT, are inserted into the BN on basis of the following: (a) the leaf nodes are independent of each other. Each node appears only once in the tree and two different nodes representing exclusive failure modes of the same component are connected with an XOR gate node, such as the states of valve: open and closed; (b) the FT nodes are interconnected by links, so that they form a directed tree.

In brief, the 6 steps in converting a BN to FT are [19]: 1. Create a corresponding node in the Bayesian network for each event in the fault tree; 2. Set the name and identifier of the corresponding node in the Bayesian network using those defined in the fault tree; 3. Assign to each node of the Bayesian network the corresponding different states, such as failure and success; 4. Connect those nodes of the Bayesian network as they are connected in the fault tree; 5. The root nodes of the Bayesian network correspond to the event nodes of the fault tree prior probabilities according to their respective states; 6. All the nodes that have parent nodes in

the Bayesian network need conditional probability tables, which can be obtained from statistical data and expert experiences. This conversion algorithm however fails to stress the point where ‘common failure’ exist among nodes. Again, it fails to provide a re-numbering method when it comes to using its software to avoid getting wrong results and to construct the conditional probability table of posterior probability accordingly. The next section presents an illustrative example of converting fault tree to Bayesian network and presents results under causal reasoning.

**4 ILLUSTRATIVE EXAMPLE: DRY DOCK GATE FAILURE ANALYSIS**

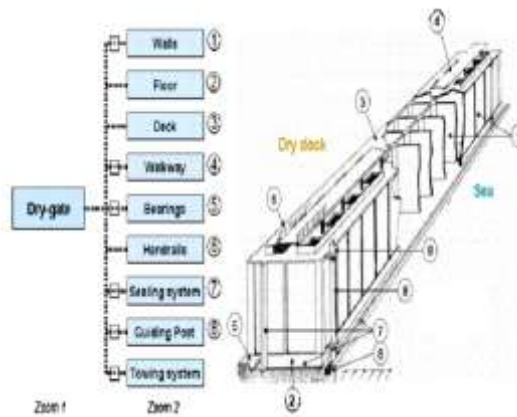
In this illustrative study, FTA of a dry dock gate failure is constructed from the failure mode effect cause analysis of the original model established by [3] for detailed analysis. A dry dock gate seen under construction is shown in Figure 8, which reflects the size of this critical component in graving dry dock. The observation and functional lists of subcomponents of dry dock gate failure (DDGF) are seen in Figure 9 In risk analysis, a better understanding is given to designers and construction engineers regarding which subcomponents require more attention

**4.1 Dry Dock Gate Failure Analysis**

Using FMECA methodology, the whole dock gate is assessed. This approach begins with a functional study of the system (integrating all its structural components and equipment), and covers a thorough identification and quantification of the potential failure modes. This process is called ‘hazard identification’. The block diagram of DDGF highlighted in Figure 10 includes environment, solicitation, geometry or material. From the observation list, a total of 86 different potential failure modes taking into account all components and all expected functions were identified.



**Figure 8: Dry dock gate under construction**



**Figure 9: Dry dock gate block diagram**

These are then quantified to find the critical ones. The most critical risks identified are [22]: (a) collapse of the dock gate caused by a resistance loss of passive re-enforcement, located in the wall on the dry dock side, and due to corrosion (mostly chloride attack); (b) collapse of the walkway caused by resistance loss of the main beams due to corrosion (chloride attack and carbonation); (c) dysfunctional bearings due to degrading properties. Constructing a fault tree from these observations, three failures: wall failure (*F3*), walkway failure (*F2*) and dysfunctional bearings (*F1*) are considered as sub-top events. Sub-event dysfunctional bearings can be caused by overheating (*Q1*) and lubrication failure (*Q2*). The causes of overheating are spalling (normal fatigue failure) (*E1*) and resistance loss in hardness (*E2*). The causes of lubrication failure are restricted oil flow (*E3*) and degradation of lubricant properties (*E4*). This deductive process is carried out in a top down fashion for wall collapse and walkway, and a total of 13 basic events, ‘E6-13’ in Table 1, is presented. The corresponding Bayesian network is mapped from the fault tree constructed by using the conversion algorithm in Section 4 A typical example of the conditional probability of node “Q” is presented in Table 2. Figure 10 and Figure 11 represent FT and BN respectively

Table 1: Description of base events



Node description			
Value %			
Level of working condition	Description of nodes that can lead to the failure of the gate	Prior	Posterior
E1	Normal fatigue failure	27.00	28.23
E2	Resistance loss in hardness	27.00	27.38
E3	Restricted oil flow	27.00	27.45
E4	Degradation of lubricant property	27.00	27.45
E5	Wind load	54.00	55.15
E6	Hydrostatic load	27.00	27.61
E7	Carbonation attack of walk way	27.00	27.68
E8	89 Chloride ion attacks on walkway	54.00	56.00
E9	89 Chloride attack on walls	54.00	56.00
E10	10 Aggregated reactivity on walls	27.00	27.72
E11	11 Gradual formation of internal cracks on walls	27.00	27.61
E12	12 Efflorescence effects on wall	54.00	53.97
E13	13 Thermal effects	54.00	55.22
Q1	Overheating	43.50	44.42
Q2	Lubricant failure	43.50	44.13
Q3	Resistance loss of wall way main beam	57.22	59.38
Q4	Walkway corrosion	57.22	59.69
Q5	Wall corrosion	59.14	59.80
Q6	Resistance loss of passive re-enforcement of walls	54.00	61.25
F1	Dysfunctional bearing	22.14	24.02
F2	Walkway failure	72.00	76.54
F3	Wall failure	73.88	78.51
R	Dock gate failure	85.45	100

Table 2: CPT for Q1

	E1	E2		
F	30	f	30	
W	70	w	70	

	Q1			
E1	f		F	
E2	f	w	f	w
F	85	80	80	10
W	15	20	20	90

**4.2 Failure Probability – No Evidence**

Assuming that the prior probabilities of all these events occurring are less than 23% and 54% when the dry dock gate operates at ground position, this means there is no fault produced by the level of working conditions. The happening probabilities of faults are listed in Table 1 under the condition of no evidence. The conditional probability table is constructed and figures entered into the *Hugin* software. An example of the conditional probability of node ‘Q1’ is seen in Table 2. All probabilities of the faults are lower than 55%. The occurrence probability of system fault P (R) is 85.5%, which means the ‘gate’ operates normally and no fault occurs. The results are the same as engineering experience.

**4.3 Failure Probability – with Evidence**

The reasoning and diagnostic ability of the DDGF network is checked under given evidence. Suppose that the system has a fault occur corresponding to ‘ $P(R) = 100\%$ ’, the new posterior probabilities results of working conditions are listed in the furthest column of Table 2. The posterior probability of E89 is 56.07%, which is the largest among those components’ failure probability under the condition of system failure. Therefore, in conclusion, E89 is the weakest part in the DDG system and needs to be strengthened in order to enhance the overall system reliability. The list from the second greatest to seventh is as follows: E13, E5, E12, E1, and E7, with values 55.22%, 55.15%, 53.97%, 28.23% and 27.68% respectively

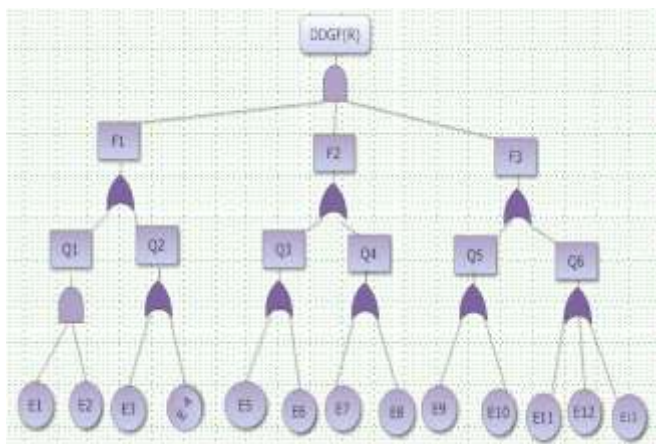


Figure 10: Fault tree of DDGF

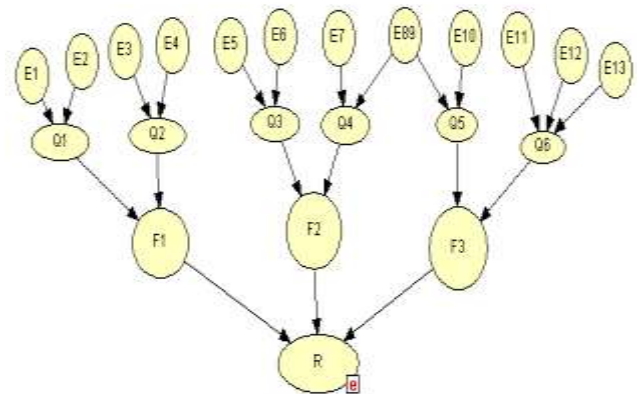


Figure 11: Bayesian conversion mapping diagram

**4.4 Casual Reasoning Calculation**

For causal reasoning, system failure probability is different in each component failure. As seen in Table 1, different components have different reliabilities in the DDG system and have their corresponding effects on the whole system reliability. Therefore, by the BN model, we can find the weak links of the system in order to provide the basis to improve the reliability of the whole system, by means of strengthening the reliability of the weak components in its design and constructing a process starting from the

order E89, E13, E5, E12, E1 and E7. To demonstrate the reliability if E89 fails 100% then failure probability of top event DDGF is 89% and if E13 fails 100% then top event probability is 87.38%, as highlighted in Figure 12.

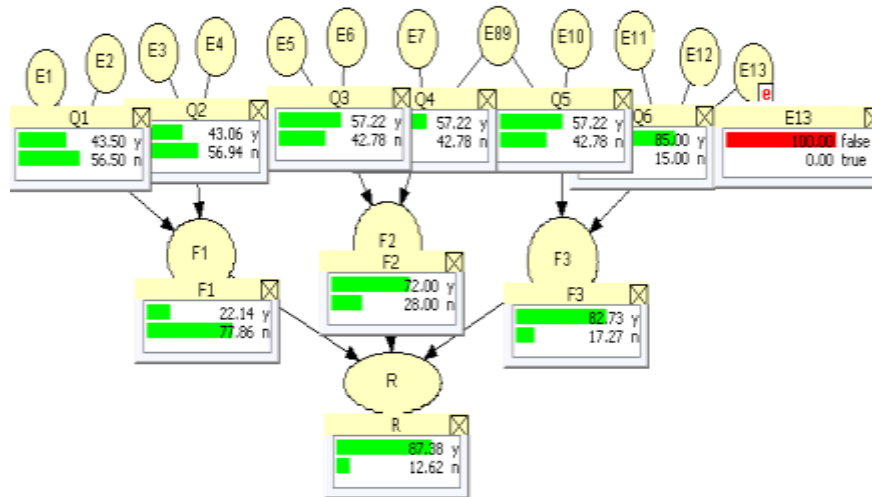


Figure 12: DDFE top event

## 5. CONCLUSION

Recommendations based on the analytic results and experience of the three main ways to prevent failure of dry dock gates, when in a ground position and during the closing and opening operation are presented. To help prevent future failures and manage resources for construction and maintenance effectively, these critical failures can help build a maintenance pattern with financial estimation beginning with reinforcing corrosion attacks on walkways and walls (E89) during the construction phase of the project in Figure 4.11 as top priority (such as passive re-enforcement corrosion, pre-stressing cable corrosion and anti-carbonation and chloride prevention attacks). The next recommendation, as indicated from the analysis results, is to channel resources into improvement of inspections of all submerged areas and underwater inspections to identify effects of salt deposits on structures (E12). In the construction phase, it is better to consider these parameters and improve on pre-stressing conditions of walls. Again, focus should continue in ranking order E5, E12, E1 and E7 as obtained from analysis. These strategic decisions are based on concrete, objective and traceable detailed analysis as illustrated in this study. However, the limitations of this simple example are when dealing with a large model, and how to construct its corresponding CPTs.

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