Safety Assessment of FPSO Turret-Mooring System Using Approximate Reasoning and Evidential Reasoning

H.S. Sii, J. Wang*, A.G. Eleye-Datubo

School of Engineering, Liverpool John Moores University, Byrom Street, Liverpool, L3 3AF, UK

J.B. Yang, J. Liu

Manchester School of Management, UMIST, Manchester, UK

Abstract

Numerous Acts of Parliament and Statutory Instruments which apply to Floating Production, Storage and Offloading (FPSO) developments in the United Kingdom Continental Shelf (UKCS), covering a wide range of issues including health, technical safety, work place safety, lifting operations, environmental protection and pollution prevention and control, are described. A comprehensive study of system safety evaluation of a typical turret-mooring system used on FPSOs is described in this paper. A safety assessment method suggested using approximate reasoning and evidential reasoning approaches is proposed in this study. Subjective safety modelling at the bottom level in a hierarchical framework is carried out using an approximate reasoning approach. The evidential reasoning method is used to combine or aggregate safety estimates at lower levels to produce the safety estimate at the system level. The four main sub-systems (Turret (T), Fluid Transfer System (FTS), Turret Transfer System (TTS) and Interfacing System (IS)) are thoroughly examined in order to perform a subjective safety assessment of the turret-mooring system.

Nomenclature

PSO: Floating Production, Storage and Offloading. A marine vessel single-point moored to the seabed allowing direct production, storage and offloading of process fluids from subset installations – usually via an internal or external turret system.

FSO: Floating Storage and Offloading vessel. It is similar to an FPSO but without production capability. Stores oil products that can be offloaded to pipelines or shuttle tankers.

FSU: Floating Storage Unit. It is a generic term for floating installations including FPSOs and FSOs.

Single Point Mooring (SPM): Mooring to the seabed from a single location on a Floating Production Unit, usually via catenary's mooring and involving a number of anchor chains, buoyancy aids and flexible risers. Single location in this context refers to the turret.

Turret: A cylindrical single point mooring system geo-stationary with the seabed allowing rotation of the FPSO or FSU vessel in response to wave and wind conditions (weathervaning).

Weathervaning: Rotation of the ship about the turret in response to wind, sea and climate conditions.

Introduction

During the 1990's there was an increasing move in the North Sea sector to subset and deepwater production with the use of floating production and storage systems. A key innovative technology is the use of Floating Production, Storage and Offloading (FPSO) vessels and other Floating Storage Units (FSUs). They are either purpose built or converted from tankers or bulk carriers. The term FSUs may also encompass simpler systems such as storage and offloading buoys. An integral part of such systems is a turret-mooring system that keeps the vessel on station via single-point mooring and allows the vessel to rotate in response to weather conditions. In 1981 the first FPSO world-wide was installed. This technology has become established relatively quickly since the first FPSO (Petrojarl I) entered UK waters

* Corresponding author, email: j.wang@livjm.ac.uk.

in 1986 and there has been considerable evolution in design to meet the specific environment conditions of the North Sea. Previously there has been little historical information and guidance available pertaining to maintenance standards, best practice, risk and reliability to Health and Safety Executive (HSE) inspectors as well as to designers and safety analysts. There are currently 14 FPSOs operating in UK waters. It is pertinent to note that most current FPSOs operating in UK waters were installed only in the late 1990s and many of the advances in turret-mooring design have come from Norway with innovative advances in swivel design from both the UK and Norway.

The first FPSOs came into service in the Far East and South America in the early 1980s as a cost-effective solution to the exploitation of small and marginal fields to extend production in existing fields or allow early production in new fields. There are particular advantages in using FPSOs in fields with short field lives where the cost of investment in pipelines, structures and field abandonment would be relatively high. These operated in shallow water (less than 150m deep) and in good climatic conditions. The 1990s saw considerable advances in design and application of FPSOs with more than 60 FPSO vessels now operational world-wide, many in severe climates and deep water (up to and exceeding 1000m).

An FPSO comprises a vessel with integral process plant, moored to the seabed and attached to risers from subset wells. Two photos of FPSO are shown in Figures 1 and 2. Production fluids flow up the flexible risers to the turret-mooring system where they are transferred to the process plant on the vessel by a swivel or other fluid transfer system. They are then processed and their products stored in tanks on board or exported. The vessel is usually equipped with the facility to offload oil products to subset installations, pipelines, storage buoys or storage vessels. The FPSO is an adaptation of simpler storage vessel technology and the use of mooring buoys for transferring production fluids from wells and subset installations.

The first generation of these early vessels was spread-moored with the risers feeding into a simple porch at mid-ship. In most locations spread-mooring is not practicable and a single point mooring is desirable to allow the vessel to weathervane, adjusting to wave and climate conditions. A turret-mooring system is an integral part of most modern FPSO systems, and the method of providing single-point-mooring. This swivels to provide effective weathervaning effect, maintain the system on station and allow fluid transfer from the risers to the process plant onboard regardless of the external environmental situations such as severe weather and wave conditions.

Advances in FPSO technology both in design and operations have allowed vessels to operate in increasingly severe environmental conditions, deeper water and to handle higher pressures and more wells. In the initial FPSO designs an external turret with a simple swivel connected to a flexible riser was commonly used. Complex multiple swivel assemblies with turrets internal to the ship are used in more recent design; in some cases, production fluids are handled from multi-wells (30 or more wells). Such designs of turret system are complex and may often include multiple flexible riser connections, pipes for process fluid and well injection, multiple seals, valves, initial separation assemblies, pig launchers and securing bolts. The consequences of failure of this type of design are clearly more severe than for a simple swivel joint. Many FPSOs have a design life of 25 years or more and there are strong cost incentives to the operator to maintain the FPSO on station.

The turret-mooring technology is relatively new in the UK and Norwegian sectors although more extensive information exists in Brazil where much of the present deepwater technology was pioneered. Most UK operators now have at least one FPSO in operation and they have gone through somewhat of a learning curve on reliability during initial operation. Experience is more extensive in simple swivel joints in buoys: these have been used in the UK sector for a number of years and formed the initial basis for conventional “Bluewater” turret design as opposed to the “Tentech” central turret designs, which originated later in Norway. The limited number of generic turret system design is advantageous in allowing experience and improvements to be passed on to future developments; but disadvantageous in that problems may become generic across FPSO operations.

This paper provides an independent assessment of established and emerging designs of turret and swivel systems for FPSOs and FSUs. This paper should also provide information for evaluation of safety cases, assessing new designs, and raising the level of awareness of safety issues in this rapidly evolving technology.

The basis for this paper has been a thorough review of FPSO and FSU turret-mooring systems including consultation with turret and fluid transfer system manufacturers. A system based approach has been used defining generic turret system types, the boundaries between systems, common systems and unique features for individual turret designs. This has produced a comprehensive guidance document of FPSO turret systems, their failure modes and inspection and maintenance practices. General issues such as ship structure and turret location are discussed together with current regulatory and certifying requirements.

A subjective safety assessment has been conducted for standard turret designs and design variants. This is to identify critical components, safety concerns and relevance of safeguard strategies such as inspection, maintenance and condition monitoring employed to ensure integrity.

FPSOs and FSUs have become established relatively quickly in North Sea operations. There are a number of generic turret design types, yet there is still considerable evolution in design and an increasing number of design and manufacturing companies involved in the market. There are specific challenges. The first one is the accessibility of information, some of which manufacturers may consider proprietary. The second one is that there is a need to identify generic technology and features which are design specific. Finally HSE and offshore operators have limited historical data on reliability, given the speed at which the technology has been exploited. In view of these constraints, a subjective method is suggested in this paper to carry out risk analysis of a turret-mooring system.

Regulatory Framework

There are numerous Acts of Parliament and Statutory Instruments which apply to FPSO developments in the United Kingdom Continental Shelf (UKCS), covering a wide range of issues including health, technical safety, work place safety, lifting operations, environmental protection and pollution prevention and control. The main item of legislation is the Offshore Installation (Safety Case) Regulations, SI 1992/2885 (HSE 1992). The Safety Case Regulations are goal-setting regulations made under the Health and Safety at Work Act, 1974 (HSE 1974). The key requirement of the Safety Case Regulations governing design is that all hazards with the potential to cause major accidents are identified, their risks evaluated, and measures taken to reduce risks to persons to as low as reasonably practicable (ALARP).

The Safety Case Regulations are backed up by the Offshore Installations (Prevention of Fire and Explosion, and Emergency Response) Regulations, PFEER, 1995 (S11995/734) (HSE 1995), the Management of Health and Safety at Work Regulations (S11999/3242) (HSE 1999a) and the Offshore Installations and Wells (Design and Construction) Regulations, DCR, 1996 (SI1996/913) (HSE 1996).

The main item of legislation dealing with environmental issues is the Offshore Petroleum Production and Pipelines Act (Assessment of Environmental Effects) Regulations 1999 (SI1999/360) (HSE 1999b). The Merchant Shipping Act 1979 (HMSO 1979) and the Merchant Shipping (Prevention of Oil Pollution) Regulations 1996 (SI1996/2154) (HMSO 1996) apply the requirements of MARPOL 73/78 (IMO 2002) on matters of marine pollution with additional UKCS-specific instructions.

It is important to note that the Design and Construction Regulations 1996 require design to be based on current good engineering practice, which is appropriately risk-based. Compliance with the existing codes, standards and guidance may not be sufficient to meet the regulatory requirements.

Codes and Standards

International codes and standards

Several international design codes for floating production systems are undergoing final review or have recently been released.

The API (American Petroleum Institute) Recommended Practice for Planning, Designing and Constructing Floating Production Systems RP 2FPS has the widest scope, covering ship-shaped, column stabilized and spar unit design. It also covers the complete floating production system including production facilities, risers and subset, and export system design (API 2001). The code is a high-level document and relies heavily on reference to appropriate sections of existing API codes, classification society rules and United States Coast Guard/Mines and Minerals Service documents to provide the detailed design guidance. Use of the API document for UKCS guidance would need to recognize the special requirements of the UKCS harsh environment and the legislative framework.

ISO/WD 19904 Offshore Structures – Floating Systems (ISO 2003) and NORSOK Standard N-004 Design of Steel Structures (NORSOK 2000) both focus on structural and marine design aspects. A review and comparison of API and these two design standards has been carried out by the HSE under Review of API RP 2FPS, OTO 2001-006 (HSE 2001).

Use of Classification Societies' Rules

Classification is not mandatory for an FPSO in the UKCS since design is governed by the Safety Case Regulations, PFEER regulations and DCR Guidance. However, most FPSO owners choose to build their vessel to classification society standards and some also choose to maintain class in service for insurance, mortgage and marketing purposes.

The following classification societies have recently issued new rules for the classification of floating production units:

Lloyds Register (LR): Rules and Regulations for the Classification of a Floating Installation at a Fixed Location, July 1999 (LR 1999).

American Bureau of Shipping (ABS): Building and Classing Floating Production Installation, June 2000 (ABS 2000a) and Guide for Building and Classing Facilities on Offshore Installations, June 2000 (ABS 2000b).

Det Norske Veritas (DNV): Offshore 2000 Rules for Classification of Floating Production and Storage Units, OSS – 102, January 2001 (DNV 2001).

Classification can use either of the following:

- Prescriptive approach, where the class rules are mainly based on the results of many years' operating experience. These rules are useful in providing a framework for rapidly generating an initial design and have the additional advantage of being familiar to shipyards. This design can then be subject to more rigorous analysis and risk assessments.
- Risk-based approach, which can be based on the safety case information. All three classification societies LR, ABS and DNV are prepared to provide risk-based classification and have recently issued guidelines on this approach.

The owner/duty holder has to advise the classification society at the outset which of the above approaches is being used and the way in which the risk assessment will be conducted and the results applied to the design of the FPSO.

Generally class can be applied to the complete floating production system or just to the hull and critical marine systems. On the other hand, the production systems can be designed to internationally recognized codes. Owing to the rich past experience the classification societies' rules address marine and structural areas in better detail than production/utilities system areas. This is to be expected because of the societies' background in ship classification.

Client and Classification Society Roles

The role of the classification society needs to be clearly defined by the owner/duty holder at project commencement viz. advisory only, full or part classification, whether classification is during construction only or also in service, and whether the classification society is to assist in preparing the safety case. This decision will depend on the expected benefits from the classification society and the following factors:

- Advantages of a classed vessel viz. obtaining a marine mortgage, for insurance purposes, marketing the vessel for subsequent use outside the UKCS or for general comfort factor.
- Owner's hands-on/hands-off approach to project management.
- Strength of the owner's technical design and construction supervision staff.
- Contracting strategy and its impact on need for supervision.
- Experience base and capabilities of classification society.

It should be noted that using classification society rules does not exempt or absolve the owner from preparing clear design philosophies, basis of design and functional specifications. Classification society rules and guidance are only useful in providing a good starting point which is familiar to designers and shipyards, and which reinforces owners' functional specifications. This is especially important in dealing with shipyards where functional specifications and performance standards are not widely understood.

Potential difficulties in using classification society rules are that they emphasize on safety-critical issues. They do not deal with what is production-critical and they do not encourage designers to think about long-term life-cycle issues which are especially important in harsh environment. Some difficulties may also arise over conflicts between prescriptive classification society rules and the outcome of safety cases. The resolution of these may be difficult if the vessel is to be classed.

Subsea Installation

After drilling, a wellhead valve assembly (commonly called a "Xmas tree" in the industry) will be placed on the top of each well. A "Xmas tree" is the interface between the well and the flowlines connecting it to the production facilities and controls the flow of fluids to and from the well. The wells are controlled by a hydraulic control system through a combined control/chemical injection umbilical.

Wells are located at distances from two to three kilometres from the FPSO. Pipelines run from the "Xmas tree" on each wellhead and tie into the turret of the FPSO. The subset pipeline infrastructure also includes umbilicals for the hydraulic control of "Xmas tree" valves, gas lift and chemical injection.

A combined chemical/hydraulic umbilical is provided to each field. Separate umbilical sections are provided from the base of the riser to the hydraulic control system on the FPSO.

Pipelines and Risers

Each pipeline consists of a flexible flowline lying on the seabed and a flexible riser fitted with buoyancy modules that will tie into the FPSO through the turret piping. The buoyant pipeline risers will each be arranged in a "steep wave" formation coming down from the turret, connecting into the flexible flowline lying on the seafloor. Each flexible flowline and umbilical riser is restrained in place near the seafloor by its own concrete-filled steel box, known as a clump weight. The transitional section from riser to flowline may be supported on the seafloor by means of a 6m×3m concrete mattress. The pipelines will lie on the seafloor from their riser connection to each wellhead, where other concrete mattresses may again be used to stabilise the pipeline on the seafloor.

The internal diameters of the pipelines are approximately between six and nine inches. Risers are around 300 to 400m long and flowlines are between one and three kilometres long. The umbilicals will have external diameters between five and nine inches. The umbilical risers are around 300m long and the seabed umbilicals between one and three kilometres long. It should be noted that, to minimise total umbilical length, certain umbilicals serve more than a single well.

Mooring

The mooring system consists of an internal turret, suspended from a bearing in a moonpool at the bow of the vessel, with the lower end of the turret anchored to the seabed via 3x3 composite wire/chain legs attached to piles. The arrangement allows the FPSO to weathervane freely through 360^0 around the fixed turret in response to varying weather and tidal conditions. This provides a passive mooring system, enabling the FPSO to be retained on station without any aid from thrusters or external sources. However, a single azimuth thruster is fitted to facilitate offloading operations and minimise greenwater conditions.

The main components of the mooring system are the mooring lines, which are secured to anchor piles. The mooring lines are grouped in 3 bundles. The bundles are spaced 120 degrees apart and the mooring lines within a bundle have a relative spacing of 2 degrees.

A Turret Mooring System

As described previously, there is an increasing move in the North Sea sector to subset and deepwater production and the exploitation of marginal fields. A key technology is the use of FPSO vessels and other FSUs in place of conventional fixed oil platforms.

Function of a Turret System

Figure 3 shows the generic sub-systems within a typical turret system. The turret system performs four main functions in a typical FPSO:

- Maintaining the vessel on station through single mooring.
- Allowing weathervaning or rotation of the vessel to adjust to climate conditions.
- Fluid transfer from the risers to the process plant.
- Providing transfer of electrical, hydraulic and other control signals.

Figure 4 provides a schematic diagram showing the interfaces for an FPSO turret and the areas of internal and external load transfer. An FPSO turret system contains the following three main systems:

- The turret itself.
- A fluid transfer system, usually a multi-path swivel to transfer production fluids to the process plant on the vessel.
- Turret transfer system, intermediate manifolding, which provides a link between the turret and the FTS. The TTS is often referred to more generally as the turnable or turnable manifolding.

Weathervaning

An advantage of a turret system over other options for floating installations such as spread-mooring is that it allows the vessel to rotate and adopt the optimum orientation in response to weather and current conditions. This rotation of the vessel about the turret is known as weathervaning.

In most cases the vessel can freely rotate through 360 degree; known as free weathervaning. If the rotation is restricted this is described as partial weathervaning. The latter is the case for turrets with a drag chain for fluid transfer, which can only rotate +/- 270 degrees in either direction.

Parts of a Turret System

In the context of this paper the turret system is considered in the following four parts:

- Turret (T): This provides the single-point mooring and allows weathervaning of the vessel. It includes the turret shaft, turret casing, main and lower bearings and the mooring spider.
- Fluid Transfer System (FTS): This is typically a multiple swivel assembly. It transfers the process fluids and other signals from the turret to the process plant on the vessel. It is positioned above the turret and linked via the turret transfer system.
- Turret Transfer System (TTS): This refers to the intermediate manifolding linking the turret and the FTS. Positioned on a turnable on top of the turret. It rotates with the turret. It is otherwise referred to as the turnable or turnable manifolding.
- Interfacing systems (IS): This includes swivel access structure, mooring lines and flexibles below the turret and other ancillary equipment.

Interfaces

There are four main external boundaries separating the turret system from the vessel. These are important from a safety and operational standpoint as they are all points of load and/or hydrocarbon transfer:

- Fluid Transfer System to ship (to process plant).
- Main turret bearing.
- Lower turret bearing and cavity containing moonpool or turret cavity (moonpool refers to the vessel structure adjacent to the turret and the access space between the turret and vessel. It is partially filled with seawater).
- Mooring spider or mooring buoy (disconnectable) to mooring lines and flexible risers.

The interface between the FTS and the process plant on the vessel is known as the FPSO/turret interface.

In addition there are internal interfaces within the turret system:

- FTS to TTS.
- T to TTS.
- Turret shaft to mooring buoy or spider.

Usually flexible risers connect the swivel to the FPSO/turret interface.

Another important interface on an FPSO from a safety standpoint is between the marine and offshore structures. This is usually considered to be at deck level. In this paper the turret system is considered to be part of the offshore structure.

Load Transfer for a Turret System

The turret system will encounter significant loading from the single point mooring from waves and current, and from the weathervaning FPSO vessel. The external interfaces represent the areas of load transfer. For a typical turret system the areas of load transfer are as follows:

- Torque arms to swivel
- Main turret bearing

- Lower bearing pads
- Connections to single point mooring
- Bend-stiffeners on flexible risers

Where the turret includes a separate mooring spider, or mooring buoy in the case of disconnectable systems, then there will be significant load transfer across this internal interface. The main bearing is the main area of load transfer from turret to the vessel including both axial and radial loads. The lower bearings, usually pads, take much lower loading. The vessel structure adjacent to the turret cavity can encounter significant ovality and loads and is a common area for development of cracking.

A Safety Model - a Framework for Modelling System Safety Using Approximate Reasoning and Evidential Reasoning Approaches for Risk Analysis

It is worth noting that many typical safety assessment approaches may have some problems for use in situations where there is a lack of information, past experience, or ill-defined situation in risk analysis (Wang and Ruxton 1997). A generic framework for modelling system safety using approximate reasoning and evidential reasoning approaches is depicted in Figure 5. It may provide a solution as it emulates the reasoning process for synthesising human expert judgments within a specific domain of knowledge, codes and standards based on the guidelines and company policy using an approximate reasoning approach. In addition, an evidential reasoning approach is used in the later stage of the framework to deal with safety synthesis of the system with complexity involving multi-experts, or multi-attributes, or a combination of both in a hierarchy. It is worth noting that the evidential reasoning approach used here is different from most conventional MADM (multiple attribute decision making) methods. Firstly, it employs a belief structure to represent an assessment as a distribution instead of as a single numerical score. Secondly, it aggregates degrees of belief rather than scores. In this way, the evidential reasoning approach can preserve the qualitative feature of subjective criteria in the process of criteria aggregation.

The proposed framework for modelling system safety for risk analysis, as shown in Figure 5, consists of five major components. The first three components outline all the necessary steps required for safety evaluation at the bottom level of a hierarchical system (i.e. each cause to technical failure) using an approximate reasoning approach. The fourth component describes the step involved in synthesising the estimates thus obtained in the first three components, using an evidential reasoning approach to synthesise safety at higher levels (this is to integrate all the possible causes to a specific technical failure, or estimates made by a panel of experts) of an engineering system. An evidential reasoning approach is used to deal with hierarchical evaluation propagation issues without any loss of useful information. The last component describes the ranking and interpretation of the final safety synthesis of a system.

The major steps of the key components used in the framework are outlined as follows:

Component # 1: Identification

- Identify all the anticipated causes/factors to technical failure of an engineering system.

Component # 2: Definition

- Define fuzzy input variables (***failure rate***, ***consequence severity*** and ***failure consequence probability*** (probability that given the occurrence of the failure, possible consequences happen)) to describe the potential risk linguistically.
- Define fuzzy output/solution variables (i.e. safety estimates).
- Select the type/types of fuzzy membership function used to delineate each input variables, and provide interpretation for each fuzzy set of each variable (in any form shown in Figure 6(a) – (d)).

Component # 3: Development of a safety model

- Construct the rule base.
- Select fuzzy reasoning/inference mechanism.
- Aggregate resultant judgments with respect to all input variables for a particular cause to technical failure.
- Create resultant safety estimate using an approximate reasoning method.
- Normalise safety estimates.
- Assign relative importance of each expert.

Component # 4: Safety synthesis

- Perform multi-expert safety synthesis in a hierarchy using the evidential reasoning approach.
- Perform multi-attribute safety synthesis using the evidential reasoning approach.

It is worth noting that in this component, in order to achieve a more effective and logical evaluation process, it is necessary to break down the complex systems into simpler sub-systems in a hierarchical manner. The hierarchical framework of attributes or experts is used to guide the overall evaluation of multi-attributes or multi-experts or a combination of multi-attributes-multi-experts synthesis problems.

Component # 5: Ranking and interpretation of results

- Calculate overall risk level ranking index.
- Rank potential causes based on their ranking index values.
- Or perform multi-attribute-multi-expert safety synthesis.

Subjective assessment (using linguistic variables instead of ultimate numbers in probabilistic terms) may be more appropriate to conduct analysis on the three parameters (*failure rate*, *consequence severity* and *failure consequence probability*) as they are always associated with great uncertainty, especially for a novel system with a high level of innovation. Thus, these three parameters are represented by natural languages, which can be further described by different types of membership functions as decided according to the situation of the case of interest.

Safety estimate is the only output fuzzy variable used in this study to produce safety evaluation for each cause to a technical failure at the bottom level of a hierarchical system. This variable is also described linguistically. In safety assessment, it is common to express a safety level by degrees to which it belongs to such linguistic variables as "*poor*", "*fair*", "*average*", and "*good*" that are referred to as safety expressions. The output set can be defined using fuzzy safety estimate sets in the same way as the fuzzy inputs.

The fuzzy membership functions are generated utilising the linguistic categories identified in the knowledge acquisition and consisting of a set of overlapping curves. Seven levels of linguistic variables may be used for ***failure rate***; five levels for ***consequence severity***, seven levels for ***failure consequence probability*** and four levels for ***safety estimate***. The literature search indicates that four to seven levels of linguistic variables are commonly used to represents risk factors in risk analysis (Bell and Badiru 1996) (Wang 1997). It is possible to have some flexibility in the definition of membership functions to suit different situations. The application of categorical judgments has been quite positive in several practical situations (Wang et al. 1995). It is also usually common and convenient for safety analysts to use categories to articulate safety information.

When describing ***failure rate***, ***consequence severity, failure consequence probability*** and ***safety estimates***, a linguistic variable may then be assigned with a membership function to a set of categories with regard to the particular condition. Typical linguistic variables for ***failure rate***, ***consequence severity, failure consequence probability*** and ***safety estimate*** are defined and characterised as follows:

Failure rate describes the failure frequencies in a certain period of time, which directly represents the number of failures anticipated during the design life span of a particular system or an item. Table 1 describes the range of the frequencies of the failure occurrence and defines the fuzzy set of ***failure rate***. To estimate the ***failure rate***, one may choose to use such linguistic variables as "*very low*", "*low*", "*average*", "*frequent*" and "*highly frequent*". Figure 7 shows the fuzzy ***failure rate*** set definition.

It is noted that the evaluation criteria for ***failure rate*** can be modified according to different requirements in codes and standards and different aspects of offshore platforms such as fire, explosions, structure and safety system.

Consequence severity describes the magnitude of possible consequences, which is ranked according to the severity of the failure effects. One may choose to use such linguistic variables as "*negligible*", "*minor*", "*moderate*", "*severe*" and "*catastrophic*" (Sii et al. 2004). The fuzzy ***consequence severity*** set definition is shown in Figure 8. Table 2 shows the criteria used to rank the ***consequence severity*** of failure effects. The fuzzy ***failure consequence probability*** set definition is depicted in Figure 9 and the criteria used to describe the ***failure consequence probability*** are shown in Table 3.

With reference to the above fuzzy descriptions of ***failure rate, consequence severity*** and ***failure consequence probability***, it may be observed that the linguistic variables are not exclusive, as there are intersections among the defined linguistic variables describing ***failure rate, consequence severity*** and ***failure consequence probability***. Inclusive expressions may make it more convenient for the safety analyst to judge a safety level. Overlapping functions are used to represent various linguistic variables for all attributes because the experts and the literature concurred that in the analysis of the risks associated with a failure event/mode, the risk levels may have "grey" or ill-defined boundaries (Bell and Badiru, 1996).

Several sources such as historical records, operator's experience, statistical data, expert judgment, etc. can be used to derive the fuzzy rules. These approaches are mutually supporting each other and a combination of them is often the most effective way to determine the rule base. In the statistical data and information analysis the fuzzy rules may be derived based on statistical studies of the information in previous incident and accident reports or database systems. In-depth literature search may also be helpful. Skilled human analysts often have a good, intuitive knowledge of the behaviour of a system and the risks involved in various types of failures without having any quantitative model in mind. Fuzzy rules provide a natural platform for abstracting information based on expert judgments and engineering knowledge since they are expressed in a linguistic form rather than numerical variables. Therefore, experts often find fuzzy rules to be a convenient way to express their knowledge of a situation.

In practical applications the fuzziness of the antecedents eliminates the need for a precise match with the inputs. All the rules that have any truth in their premises will fire and contribute to the fuzzy conclusion (***safety estimate***). Each rule is fired to a degree at which its antecedent matches the input. This imprecise matching provides a basis for interpolation between possible input states and serves to minimise the number of rules needed to describe the input-output relation. There are 245 rules in the rule-base for the case study. Rule#1 reads as follows:

IF **failure rate** is very low *AND* **consequence severity** is negligible *AND* **failure consequence probability** is highly unlikely *THEN* **safety estimate** is "*Good".*

The importance of fuzzy *IF-THEN* rules stems from the fact that human expert-judgments and engineering knowledge can often be represented in the form of fuzzy rules. Rules based on these types of linguistic variables are more natural and expressive than numerical numbers and criticality calculations. It is clear that such rules can accommodate quantitative data such as ***failure rate, failure consequence probability*** and qualitative and judgmental data such as the ***consequence severity***, and combine them consistently in safety evaluation.

The criteria of selecting fuzzy reasoning/inference mechanisms are always subjective issues and mainly based on the user's preference. The general approach adopted is similar to that used in fuzzy expert and fuzzy control systems. A Mamdani-type inference engine is used in this study. The details of fuzzy reasoning can be found in (Sii et al. 2004).

The first module of fuzzy inference operation is to take the inputs and determine their appropriate fuzzy sets via membership functions. Inputs can be represented by one of the following membership functions to suit the conditions under study:

- A single deterministic value with 100 % certainty (see Figure 6(a)).
- A closed interval defined by an equally likely range (see Figure 6(b)).
- A triangular distribution defined by a most likely value, with lower and upper least likely values (see Figure 6(c)).
- A trapezoidal distribution defined by a most likely range, with lower and upper least likely values (see Figure 6(d)).

They can be either a crisp numerical value (for the single deterministic value), a range (for closed interval), a most likely value (for triangular distribution), a most likely range (for trapezoidal distribution) limited to the universe of discourse of the input variable (in this case the interval is between 0 and 10). The output is a membership function in which fuzzy membership degrees are associated with the linguistic set for failure rate, consequence severity or failure consequence severity. Such membership degrees are always between *0* and *1.0*. Fuzzification of the input parameter amounts to either a table lookup or a function evaluation.

Relative weights assignment

It is highly unlikely for selected experts to have the same importance; weights of importance need to be utilised. The assessment of weight for each expert is an important decision for the analyst to make in view of the safety of the system under scrutiny. Each expert is assigned with a weight to indicate the relative importance of his or her judgment in contributing towards the overall safety evaluation process. The analyst must decide which experts are more authoritative. Weights are then assigned accordingly.

Case Study: Technical Risk Analysis of a Turret Mooring System Used on an FPSO

The main hazards associated with an FPSO were shown to be process accidents and collision accidents. Fires and explosions in the cargo tanks were not considered to be major contributors to risk, but are important aspects for crude oil carriers and were also considered relevant for FPSOs. A specific feature in FPSOs is the close proximity of the process plant on deck immediately above the storage tanks. Offloading was not considered as a high risk activity.

In this section, a preliminary safety assessment is carried out on risk introduced by the malfunction of individual components associated with various sub-systems of a typical turret-mooring system. Only technical failure caused risk is assessed here, though operational failure has been also recognised as one of the major events leading to collision. In this case study, there is only one expert taking part in the safety assessment. For the purpose of safety modelling, it is assumed that each input parameter (***failure rate***, ***consequence severity***, and ***failure consequence probability***) will be fed to the proposed safety model in terms of fuzzy membership functions in any one of the four forms described in Figure 6 (a) – (d).

The selection of forms of membership function by an expert is dependent upon subjective judgment made pertaining to the level of ambiguity and uncertainty associated with the case as perceived by the expert.

The safety critical elements were considered for the FPSO to be the engine room, process plant and the turret. In this paper only turret-mooring system is to be covered. The generic turret-mooring system shown in Figures 3 and 4 as well as hierarchically in Figure 10 is chosen as the system to be assessed by using the suggested framework. It consists of T, FTS, TTS and IS.

The expert judgment made on the three input parameters (***failure rate***, ***consequence severity*** and ***failure consequence probability***) using different forms of membership functions for representing technical failure of all the components associated with each sub-system is shown in Table 4(a)–(d).

Example

An example is used to demonstrate the rule evaluation processes in the fuzzy inference engine of the proposed safety model for risk analysis. The evaluation made by an expert on technical risk caused by the flexible riser and connections failure is used here to demonstrate the procedure involved in fuzzy inference engine. The “truth value” of a rule is determined from the conjunction of the rule antecedents. With conjunction defined as ‘minimum’, rule evaluation then consists of determining the smallest (minimum) rule antecedent, which is taken to be the truth value of the rule. This truth value is then applied to all consequences of the rule. If any fuzzy output is a consequence of more than one rule corresponding to a particular safety expression, that output is set to the highest (maximum) truth value of all the rules. The detailed computation work is shown in (Sii et al. 2004). The 245 rules in the rule base that are used in this study are listed in Appendix A of this paper.

Safety estimate judged by an expert on technical risk of a typical turret system due to possible failure of its sub-system # 1 (turret system) caused by one of its components (flexible risers and connections) is shown in Table 5.

With reference made to Table 5, 12 rules are participated in the fuzzy inference operations. The “truth values” for Rule # 130 are: *0.4* for ***failure rate***, *1.0* for ***consequence severity***, *0.5* for ***failure consequence probability***. Upon application of “min” operator over these “truth values” for various antecedents, *0.4* is taken as the “truth value” of this particular rule and it is then applied to the fuzzy output (*safety estimate*). The obtained safety estimate reads *0.40 ‘fair’*. The similar computation is performed for the other rules as depicted in Table 5. The aggregated ***safety estimate*** is as follows:

Safety estimate: *S(Flexible risers* and *connections)*= {0.0, ‘*good’*, 0.0, ‘*average’*, 0.5, ‘*fair’*, 0.85, ‘*poor’*}

After normalisation, ***Safety estimate*** is obtained as *S(Flexible risers* and *connections)*= {0.0, ‘*good’*, 0.0, ‘*average’*, 0.3703, ‘*fair’*, 0.6297, ‘*poor’*}.

The similar computation is performed for other components of sub-system # 1 and other three sub-systems using the proposed approach and results are shown in Table 6(a) – (d).

According to the generic framework shown in Figure 5, the evidential reasoning algorithm is used to synthesise the information thus produced to assess the safety of the whole system. This step is concerned with safety synthesis of a system at various configurations such as:

- 1st level multi-attribute safety synthesis - The synthesis of safety estimates of various sub-systems caused by their associated components respectively to the technical failure assessed by an expert (Figures 5 and 11), or
- 2nd level multi-attribute safety synthesis - The synthesis of safety estimates of various subsystems of a typical turret system by an expert (Figures 5 and 12).

A window-based and graphically designed intelligent decision system (IDS) based on evidential reasoning approach is used to synthesise safety estimates (Yang and Xu 2002). A multi-attribute synthesis is carried out at the bottom level (component level) and eventually progressed up to the system level.

Multi-attributes safety synthesis

Table 7 shows the results of multi-attributes safety synthesis (at sub-system level) on technical risk of a turret-mooring system due to T, FTS, TTS and IS caused technical failure, obtained using the evidential reasoning approach. The synthesis is carried out without considering the relative weights of each sub-system, that is, unity of weight (relative weights of importance configurations among the components are constant) is used.

Table 8 shows the results of safety synthesis of a turret-mooring system (at whole system level) obtained evidential reasoning approach.

Ranking

To calculate risk ranking index values associated with various causes to technical failure, it is required to describe the four safety expressions (*good, average, fair, poor*) using numerical values. The numerical values associated with the defined safety expressions can be designated by experts. Suppose K_1, K_2, K_3 and K_4 represent the unscaled numerical values associated with '*good*', '*average*', '*fair*', '*poor*', respectively. Then K_1, K_2, K_3 and K_4 can be represented as follows:

$\{K_1, K_2, K_3, K_4\} = \{1, 0.8, 0.6, 0.2\}$.

The risk ranking index value R_i associated with cause i to technical failure can be defined as follows:

$R_i = \sum_{j=1}^{4} \mu_l^j \times K_i$, $i = 1, 2, \ldots, d$ where d is the number of causes to technical failure.

Obviously, the R_i values obtained using the above expression can only show the relative risk level among all potential causes identified under study. The smallest R_i is ranked first as it deserves more attention to reduce its potential risk to ALARP (as low as reasonably practicable). The largest R_i is ranked last to draw least attention and minimum effort for risk reduction measure consideration. A smaller R_i means that cause i is having relatively higher risk level and deserves more attention at the early design stages/or the early stages of designing operational strategies.

The risk ranking for each sub-system based on the safety synthesis obtained using evidential reasoning approach is shown as follows:

R (Turret) = 0.3022

R (Fluid Transfer System) = 0.3355

R (Turret Transfer System) = 0.3663

R (Interfacing System) = 0.4000.

In this context, the ranking sequence is as follows:

Ranking = Turret (T) > Fluid Transfer System (FTS) > Turret Transfer System (TTS) > Interfacing System (IS)

Conclusions

The safety culture in many industries including the maritime sector in the UK has been dramatically changing over the last several years. In general, a "goal setting" risk-based regime has become a general flow in safety management in many industries. This has created an enormous environment of flexibility and creativity which encourages safety engineers or other personnel who are involved in safety related disciplines to employ the latest risk modelling techniques and decision making/optimisation tools while carrying out safety assessment. It may be very beneficial that many advances that have been developed and are being developed in general engineering and technology are further explored, exploited and also applied in order to facilitate risk modelling and decision making. In fact, it is widely accepted that any developed safety analysis approach should preferably be introduced into a commercially stable environment in order that the applications have the chance to become established to prove feasible, otherwise it is more likely that its full potential will not be realised. Therefore, emphasis should be directed to apply them in the maritime environment.

The main aim of preliminary risk assessment is to identify the anticipated hazards and potential major accident scenarios which could have an effect on the integrity of the FPSO and the safety of the crew. Performing the evaluation and risk assessment at this early stage will also possibly provide further action-learning opportunities which permit the design team to identify any fundamental deficiencies in the outline design of the selected concept. Moreover, this will enable the design team to explore and identify particular areas which have to be targeted during the various phases of design to prevent the occurrence of hazardous events or, if prevention is not possible, to detect events, and control and mitigate their effects. Implementation of changes is always easier and economical before detailed design gets underway. The evaluation and assessment process can be repeated to test the effectiveness of any safety improvements which might be made subsequently.

Providing that the evaluation and preliminary risk assessment have been comprehensive, the basis of design will reflect more accurately the requirements and aims of the overall design. Furthermore, a good foundation will have been laid for the preparation of the safety management system as well as design safety case.

The attempts in application of interval mathematics and possibility distribution such as approximate reasoning (based on fuzzy logic) method is a departure from conventional probability-based techniques which rely rather heavily on randomness and frequency to quantify the effects of risks on engineering systems. The proposed modelling framework offers a great potential in safety assessment and decision support of offshore systems, especially in the initial concept design stages of a relatively novel system such as a turret-mooring system where the related safety information is scanty/with great uncertainty involved or only linguistic-related information is available. Safety assessment using approximate reasoning approaches can integrate domain human experts' experience and safety engineering knowledge; at the same time information of difference properties from various sources can be transformed to become the knowledge base, used in the fuzzy logic inference process.

The results obtained from a case study on a turret-mooring system used on FPSOs have demonstrated that such a modelling framework proposed provides safety analysts and designers with a convenient tool that can be used at various stages of the design process of offshore engineering systems in performing risk analysis. The approach described forms a supplement to concepts and methodologies already in use for offshore safety assessment.

Acknowledgements

This work forms part of the projects supported by the UK Engineering and Physical Sciences Research Council (EPSRC) under grant reference numbers GR/R30624 and GR/S85504. The useful comments provided by the anonymous referees are also thanked.

References

1. ABS, American Bureau of Shipping guide for building and classing floating production installations, Houston, USA, June, 2000a.
2. ABS, American Bureau of Shipping guide for building and classing facilities on offshore installations, Houston, USA, June, 2000b.
3. API, API recommended practice for planning, designing and constructing floating production systems RP 2FPS, American Petroleum Institute, Washington DC, USA, 2001
4. DNV, Det Norske Veritas offshore rules for classification for floating production and storage units, OSS-102, Oslo, Norway, January, 2001.
5. HSE, The offshore installation (safety case) regulations, SI 1992/2885, UK, 1992.
6. HSE, The offshore installations (prevention of fire and explosion, and emergency response) regulations, PFEER, SI 1995/743, UK, 1995.
7. HSE, The offshore installations and wells (design and construction) regulations, DCR, SI 1996/913, UK, 1996.
8. HSE, Management of health and safety at work regulations, SI 1999/3242, UK, 1999a.
9. HSE, Offshore petroleum production and pipelines act (assessment of environmental effects) Regulations, SI 1999/360, UK, 1999b.
10. HSE. HSE review of API RP 2FPS, OTO 2001-006, 2001.
11. ISO, ISO/WD 19904 offshore structures – floating systems, 2003.
12. KLIR, J.G. and YUAN, B., Fuzzy sets and fuzzy logic, theory and applications, Prentice-Hall, New Jersey, USA, 1995.
13. LR, Lloyds Register of Shipping rules and regulations for the classification of a floating installation at a fixed location, London, UK, July, 1999.
14. IMO, MARPOL (73/78) (2002 consolidated edition): international convention for the prevention of pollution from ships, International Maritime Organization, London, UK, 2002.
15. MCCAULEYBELL, P. and BADIRU, A.B., "Fuzzy modelling and analytic hierarchy processing to quantify risk levels associated with occupational injuries – part 1: the development of fuzzy-linguistic risk levels". IEEE Transactions on Fuzzy Systems, Vol.4, No.2, 1996, 124-131.
16. HMSO, Merchant shipping act (ISBN: 0110978811), Norwich, UK, 1979.
17. HMSO, The merchant shipping (prevention of oil pollution) regulations 1996 (ISSN: 011062940x), Norwich, UK, 1996.
18. NORSOK, NORSOK standard N-004 design of steel structures, Norwegian Technology Centre, Oslo, Norway, 2000.
19. SII, H.S., LIU, J., WANG, J., YANG, J.B. and ELEYE-DATUBO, A.G., "The application of approximate reasoning methodology to offshore engineering design", Final Report submitted to industrial collaborators (AMEC, AMEY, EQE, HSE, Lloyds, NNC, UKOOA, etc), April, 2004, 327pages.
20. HSE, The health and safety at work act, UK, 1974.
21. UKOOA, UKOOA guidelines for the management of safety critical elements – a joint industry guide, Aberdeen, UK, September, 1996.
22. WANG, J. and RUXTON, T., "Design for safety", Journal of American Society of Safety Engineers, Vol.42, No.1, January 1997, 23-29.
23. WANG, J., "A subjective methodology for safety analysis of safety requirements specifications", IEEE Transaction on Fuzzy Systems, Vol.5, No.3, 1997, 418-430.

24. WANG J., YANG J.B. and SEN P., “Safety analysis and synthesis using fuzzy sets and evidential reasoning”, Reliability Engineering & System Safety, Vol.47, No.2, 1995, 103-118.
25. WANG, L.X., A course in fuzzy systems and control, Prentice-Hall, New Jersey, USA, 1997.
26. YANG J.B. and XU D.L., “Intelligent decision system via evidential reasoning”, Version 1.1, IDSL, Cheshire, England, 2003, http://www.e-ids.co.uk/.

Appendix A: A sample of rule base

- Rule # 1: *IF the* ***failure rate*** *is very low AND the* ***consequence severity*** *is negligible AND the* ***failure consequence probability*** *is highly unlikely THEN the* ***safety estimate*** *is good.*
- Rule # 2: *IF the* ***failure rate*** *is very low AND the* ***consequence severity*** *is negligible AND the* ***failure consequence probability*** *is unlikely THEN the* ***safety estimate*** *is good.*
- Rule # 3: *IF the* ***failure rate*** *is very low AND the* ***consequence severity*** *is negligible AND the* ***failure consequence probability*** *is reasonably unlikely THEN the* ***safety estimate*** *is good.*
- Rule # 4: *IF the* ***failure rate*** *is very low AND the* ***consequence severity*** *is negligible AND the* ***failure consequence probability*** *is likely THEN the* ***safety estimate*** *is average.*
- Rule # 5: *IF the* ***failure rate*** *is very low AND the* ***consequence severity*** *is negligible AND the* ***failure consequence probability*** *is reasonably likely THEN the* ***safety estimate*** *is average.*
-
-
- Rule # 241: *IF the* ***failure rate*** *is highly frequent AND the* ***consequence severity*** *is catastrophic AND the* ***failure consequence probability*** *is reasonably unlikely THEN the* ***safety estimate*** *is fair.*
- Rule # 242: *IF the* ***failure rate*** *is highly frequent AND the* ***consequence severity*** *is catastrophic AND the* ***failure consequence probability*** *is likely THEN the* ***safety estimate*** *is poor.*
- Rule # 243: *IF the* ***failure rate*** *is highly frequent AND the* ***consequence severity*** *is catastrophic AND the* ***failure consequence probability*** *is reasonably likely THEN the* ***safety estimate*** *is poor.*
- Rule # 244: *IF the* ***failure rate*** *is highly frequent AND the* ***consequence severity*** *is catastrophic AND the* ***failure consequence probability*** *is highly likely THEN the* ***safety estimate*** *is poor.*
- Rule # 245: *IF the* ***failure rate*** *is highly frequent AND the* ***consequence severity*** *is catastrophic AND the* ***failure consequence probability*** *is definite THEN the* ***safety estimate*** *is poor.*

Table 1: Failure rate (see Figure 7)

Rank	***Failure rate***	Meaning (general interpretation for all the systems of a type)
1,2,3	Very low	Failure is unlikely but possible during lifetime
4	Low	Likely to happen once during lifetime
5	Reasonably low	Between low and average
6	Average	Occasional failure
7	Reasonably Frequent	Likely to occur from time to time
8, 9	Frequent	Repeated failure
9,10	Highly frequent	Failure is almost inevitable or likely to exist repeatedly

Table 2: Consequence severity (see Figure 8)

Rank	***Consequence severity***	Meaning (generic marine and offshore structure/system interpretation)
1	Negligible	At most a single minor injury or unscheduled maintenance required (service and operations can continue).
2, 3	Marginal	Possible single or multiple minor injuries or/and minor system damage. Operations interrupted slightly, and resumed to its normal operational mode within a short period of time (say less than 2 hours).
4, 5, 6	Moderate	Possible multiple minor injuries or a single severe injury, moderate system damage. Operations and production interrupted marginally, and resumed to its normal operational mode within, say no more than 4 hours.
7, 8	Critical	Possible single death, probable multiple severe injuries or major system damage. Operations stopped, platform closed, shuttle tanker's failure to function. High degree of operational interruption due to the nature of the failure such as an inoperable platform (e.g. drilling engine fails to start, power system failure, turret mooring system failure) or an inoperable convenience subsystem (e.g. DP, PRS).
9, 10	Catastrophic	Possible multiple deaths, probable single death or total system loss. Very high severity ranking when a potential failure mode (e.g. collision between FPSO and shuttle tanker, blow-out, fire and explosion) affects safe platform operation and/or involves non-compliance with government regulations.

Table 3: Failure consequence probability (see Figure 9)

Rank	***Failure consequence probability***	Meaning
1	Highly unlikely	The occurrence likelihood of possible consequences is highly unlikely given the occurrence of the failure event (extremely unlikely to exist on the system or during operations).
2,3	Unlikely	The occurrence likelihood of possible consequences is unlikely but possible given that the failure event happens (improbable to exist even on rare occasions on the system or during operations).
4	Reasonably unlikely	The occurrence likelihood of possible consequences is reasonably unlikely given the occurrence of the failure event (likely to exist on rare occasions on the system or during operations).
5	Likely	It is likely that consequences happen given that the failure event occurs (a programme is not likely to detect a potential design or an operational procedural weakness).
6,7	Reasonably likely	It is reasonably likely that possible consequences occur given the occurrence of the failure event (i.e. exist from time to time on the system or during operations, possibly caused by a potential design or operational procedural weakness).
8	Highly likely	It is highly likely that possible consequences occur given the occurrence of the failure event (i.e. often exist somewhere on the system or during operations due to a highly likely potential hazardous situation or a design and/or operational procedural drawback).
9,10	Definite	Possible consequences happen given the occurrence of a failure event (i.e. likely to exist repeatedly during operations due to an anticipated potential design and an operational procedural drawback).

Table 4(a): Expert judgment of the three input parameters using different forms to address different levels of uncertainty for technical failure of sub-system # 1 (Turret (T)) caused by malfunction of its various components

Component	**Shape of membership function**	***Failure Rate***	***Consequence Severity***	***Failure Consequence Probability***
1.1 Flexible risers and connection	Triangular	{6.5, 7, 7.5}	{8, 8.5, 9}	{5.5, 7, 8}
1.2 Bolting	Single deterministic	{7.75}	{8.25}	{7.6}
1.3 Main turret bearings	Triangular	{5.5, 7.5, 9}	{7, 8.5, 10}	{5, 7.5, 9.5}
1.4 Lower bearing assembly	Closed interval	{7, 7, 9, 9}	{7.5, 7.5, 9.5, 9.5}	{7, 7, 8, 8}
1.5 Chain stoppers and tensioners	Triangular	{7, 7.5, 8}	{7.5, 8.5, 9}	{6, 7, 7.5}
1.6 Upper bearing support vessel deck	Closed interval	{5.5, 5.5, 7.5, 7.5}	{6, 6, 8, 8}	{6, 6, 8, 8}
1.7 Turret shaft	Single deterministic	{7.5}	{7.2}	{7.1}
1.8 Moonpool and turret cavity	Triangular	{6, 7, 7.5}	{6.5, 7, 8}	{4.5, 5.5, 6}
1.9 Mooring lines	Triangular	{6, 6.5, 8}	{7, 8, 9}	{6, 7.5, 8}
1.10 Mooring spinder	Trapezoidal	{6, 7, 8, 9}	{5, 7, 8, 8.5}	{6, 7, 8, 9}

Table 4(b): Expert judgment of the three input parameters using different forms to address different levels of uncertainty for technical failure of sub-system # 2 (Fluid Transfer System (FTS)) caused by malfunction of its various components

Component	**Shape of membership function**	***Failure Rate***	***Consequence Severity***	***Failure Consequence Probability***
2.1 Swivel and multi path swivel systems	Single deterministic	{7.15}	{7.95}	{7.25}
2.2 Compact swivel	Single deterministic	{7.95}	{8.25}	{7.9}
2.3 Drag chain fluid transfer systems	Triangular	{6.5, 7, 8}	{6.5, 7, 8.5}	{5.5, 6, 7}

Table 4(c): Expert judgment of the three input parameters using different forms to address different levels of uncertainty for technical failure of sub-system # 3 (Turret Transfer System (TTS)) caused by malfunction of its various components

Component	**Shape of membership function**	***Failure Rate***	***Consequence Severity***	***Failure Consequence Probability***
3.1 Corrosion	Trapezoidal	{6.5, 7, 7.5, 8}	{6, 6.5, 7, 8}	{6.5, 7, 7.5, 9}
3.2 Loss of wall thickness	Triangular	{6.5, 8, 9.5}	{7.5, 8.5, 9.5}	{5.5, 7, 8.5}
3.3 Weld root erosion	Trapezoidal	{5.5, 6.5, 9, 10}	{5.5, 7, 8, 10}	{5, 7, 8, 8.5}
3.4 Fatigue and leakage	Trapezoidal	{5, 6, 7, 8}	{5, 7, 8, 9}	{5, 6, 7, 9}

Table 4(d): Expert judgment of the three input parameters using different forms to address different levels of uncertainty for technical failure of sub-system # 4 (Interfacing System (IS)) caused by malfunction of its various components

Component	**Shape of membership function**	***Failure Rate***	***Consequence Severity***	***Failure Consequence Probability***
4.1 Cranes and winches	Closed interval	{6, 6, 8, 8}	{7, 7, 9, 9}	{6.5, 6.5, 9, 9}

Table 5: Example of safety estimate by an expert on technical risk of a typical turret system due to possible failure of flexible risers and connections of sub-system # 1

Rule #	***Failure Rate***	***Consequence Severity***	***Failure Severity Probability***	min-operator	***Safety estimate***
130	0.4	1.0	0.5	0.4	0.4 '*fair*'
131	0.4	1.0	1.0	0.4	0.4 '*fair*'
137	0.4	0.6	0.5	0.4	0.4 '*fair*'
138	0.4	0.6	1.0	0.4	0.4 '*poor*'
165	0.85	1.0	0.5	0.5	0.5 '*fair*'
166	0.85	1.0	1.0	0.85	0.85 '*poor*'
172	0.85	0.6	0.5	0.5	0.5 '*poor*'
173	0.85	0.6	1.0	0.6	0.6 '*poor*'
200	0.4	1.0	0.5	0.4	0.4 '*fair*'
201	0.4	1.0	1.0	0.4	0.4 '*poor*'
207	0.4	0.6	0.5	0.4	0.4 '*poor*'
208	0.4	0.6	1.0	0.4	0.4 '*poor*'

Table 6(a): Safety estimate by an expert on technical risk of a typical turret system due to possible failure of the associated components of its sub-system # 1

Components	***Failure Rate***	***Consequence Severity***	***Failure Consequence Probability***	***Safety estimate (normalised)***			
				Good	*Average*	*Fair*	*Poor*
1.1 Flexible risers and connections	{6, 7.5, 8}	{7.5, 8, 9.5}	{5, 6, 7}	0	0	0.3703	0.6297
1.2 Bolting	{7.75}	{8.25}	{7.6}	0	0	0	1.0
1.3 Main turret bearings	{5.5, 7.5, 9.0}	{7, 8.5, 10}	{5, 7.5, 9.5}	0	0	0.4348	0.5652
1.4 Lower bearing assembly	{7, 7, 9, 9}	{7.5, 7.5, 9.5, 9.5}	{7, 7, 8, 8}	0	0	0	1.0
1.5 Chain stoppers and tensioners	{7, 7.5, 8}	{7.5, 8.5, 9}	{6, 7, 7.5}	0	0	0	1.0
1.6 Upper bearing support vessel deck	{5.5, 5.5, 7.5, 7.5}	{6, 6, 8, 8}	{6, 6, 8, 8}	0	0.2	0.4	0.4
1.7 Turret shaft	{7.5}	{7.2}	{7.1}	0	0	0	1.0
1.8 Moonpool and turret cavity	{6, 7, 7.5}	{6.5, 7, 8}	{4.5, 5.5, 6}	0	0.1515	0.4545	0.3939
1.9 Mooring lines	{6, 6.5, 8}	{7, 8, 9}	{6, 7.5, 8}	0	0	0.4828	0.5172
1.10 Mooring spider	{6, 7, 8, 9}	{5, 7, 8, 8.5}	{6, 7, 8, 9}	0	0	0.3939	0.6061

Table 6(b): Safety estimate by an expert on technical risk of a typical turret system due to possible failure of the associated components of sub-system # 2

Components	***Failure Rate***	***Consequence Severity***	***Failure Consequence Probability***	***Safety estimate (normalised)***			
				Good	*Average*	*Fair*	*Poor*
2.1 Swivel and multi path swivel systems	{7.15}	{7.95}	{7.25}	0	0	0	1.0
2.2 Compact swivel	{7.95}	{8.25}	{7.9}	0	0	0.375	0.625
2.3 Drag chain fluid transfer system	{6.5, 7, 8}	{6.5, 7, 8.5}	{5.5, 6, 7}	0	0	0.7407	0.2593

Table 6(c): Safety estimate by an expert on technical risk of a typical turret system due to possible failure of the associated components of sub-system # 3

Components	***Failure Rate***	***Consequence Severity***	***Failure Consequence Probability***	***Safety Estimate (Normalised)***			
				Good	*Average*	*Fair*	*Poor*
3.1 Corrosion	{6.5, 7, 7.5, 8}	{6, 6.5, 7, 8}	{6.5, 7, 7.5, 9}	0	0	0.4444	0.5556
3.2 Loss of wall thickness	{6.5, 8, 9.5}	{7.5, 8.5, 9.5}	{5.5, 7, 8.5}	0	0	0.2223	0.7777
3.3 Weld root erosion	{5.5,6.5,9,10}	{5.5, 7, 8, 10}	{5, 7, 8, 8.5}	0	0	0.4286	0.5714
3.4 Fatigue and leakage	{5, 6, 7, 8}	{5, 7, 8, 9}	{5, 6, 7, 9}	0	0.2	0.4	0.4

Table 6(d): Safety estimate by an expert on technical risk of a typical turret system due to possible failure of the associated components of sub-system # 4

Components	***Failure Rate***	***Consequence Severity***	***Failure Consequence Probability***	***Safety Estimate (Normalised)***			
				Good	*Average*	*Fair*	*Poor*
4.1 Cranes and winches	{6, 6, 8, 8}	{7, 7, 9, 9}	{6.5, 6.5, 9, 9}	0	0	0.5	0.5

Table 7: Multi-attribute safety synthesis on technical risk of a turret-mooring system due to the components failure of T, FTS, TTS and IS

Sub-system	**Safety Expression**			
	Good	***Average***	***Fair***	***Poor***
Turret (T)	0.0	0.0265	0.2129	0.7606
Fluid Transfer System (FTS)	0.0	0.0	0.3389	0.6612
Turret Transfer system (TTS)	0.0	0.0397	0.3561	0.6042
Interfacing System (IS)	0.0	0.0	0.5	0.5

Table 8: Safety synthesis of a turret-mooring system (at system level) due to sub-system failures (failures of T, FTS, TTS and IS)

	Safety Estimate			
	Good	***Average***	***Fair***	***Poor***
Whole system	0.0	0.0129	0.3227	0.6644

Figure 1: A diagram of an FPSO (Petrobras P35 FPSO, 337 meters, 309,000 tons, approx. 100,000 BOPD, 850m WD)

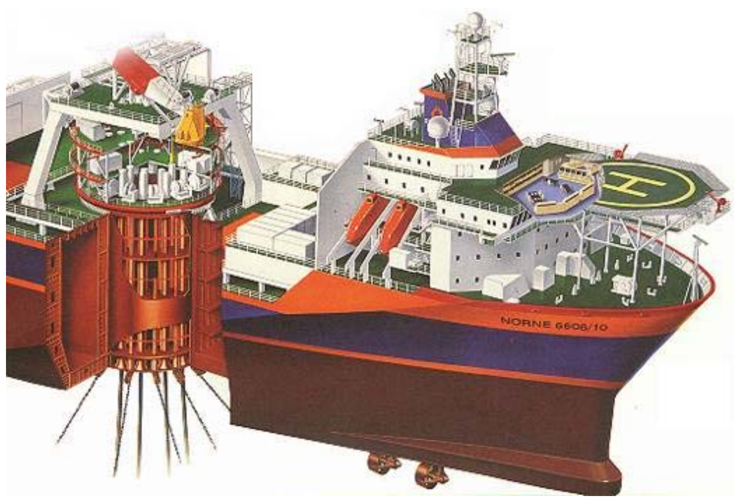

Figure 2: An FPSO with a turret system (available at www.offshore-technology.com)

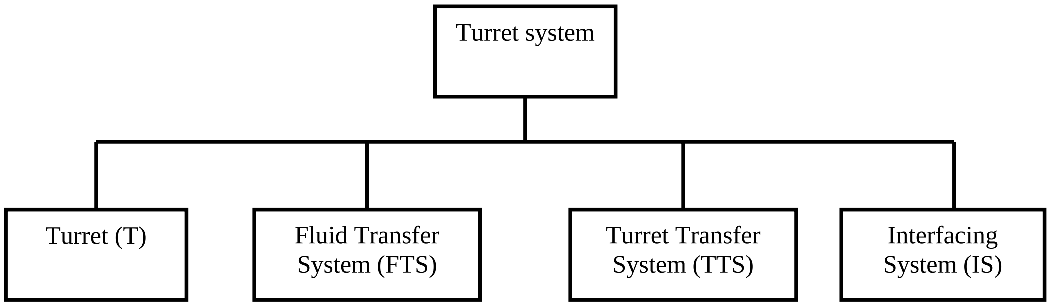

Figure 3: The generic sub-systems within a typical turret system

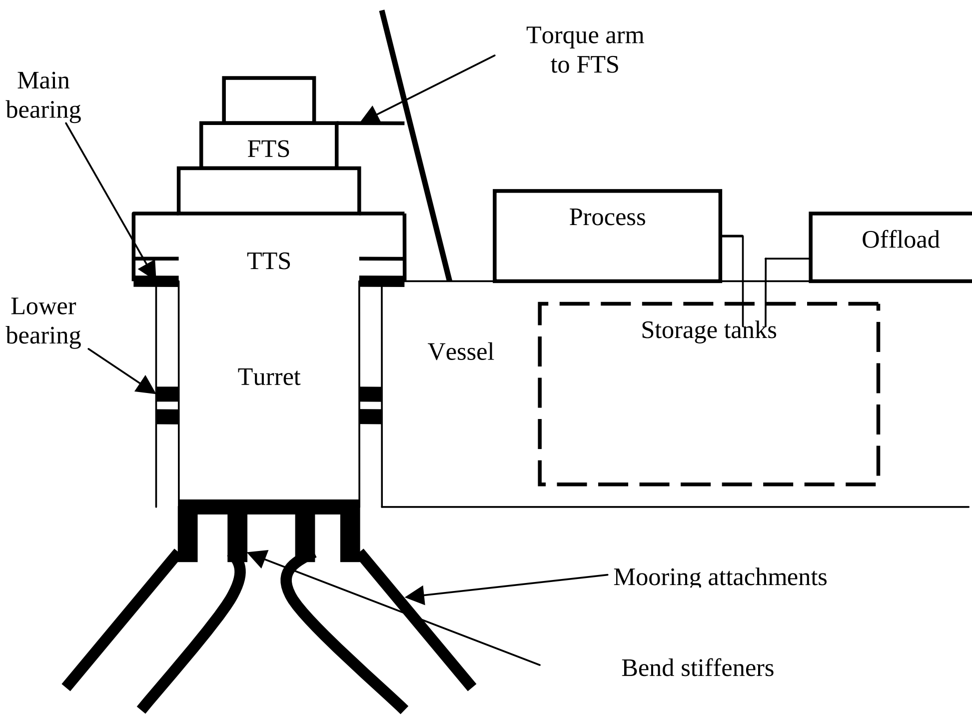

Figure 4: Schematic diagram showing the interfaces for an FPSO turret and the areas of internal and external load transfer

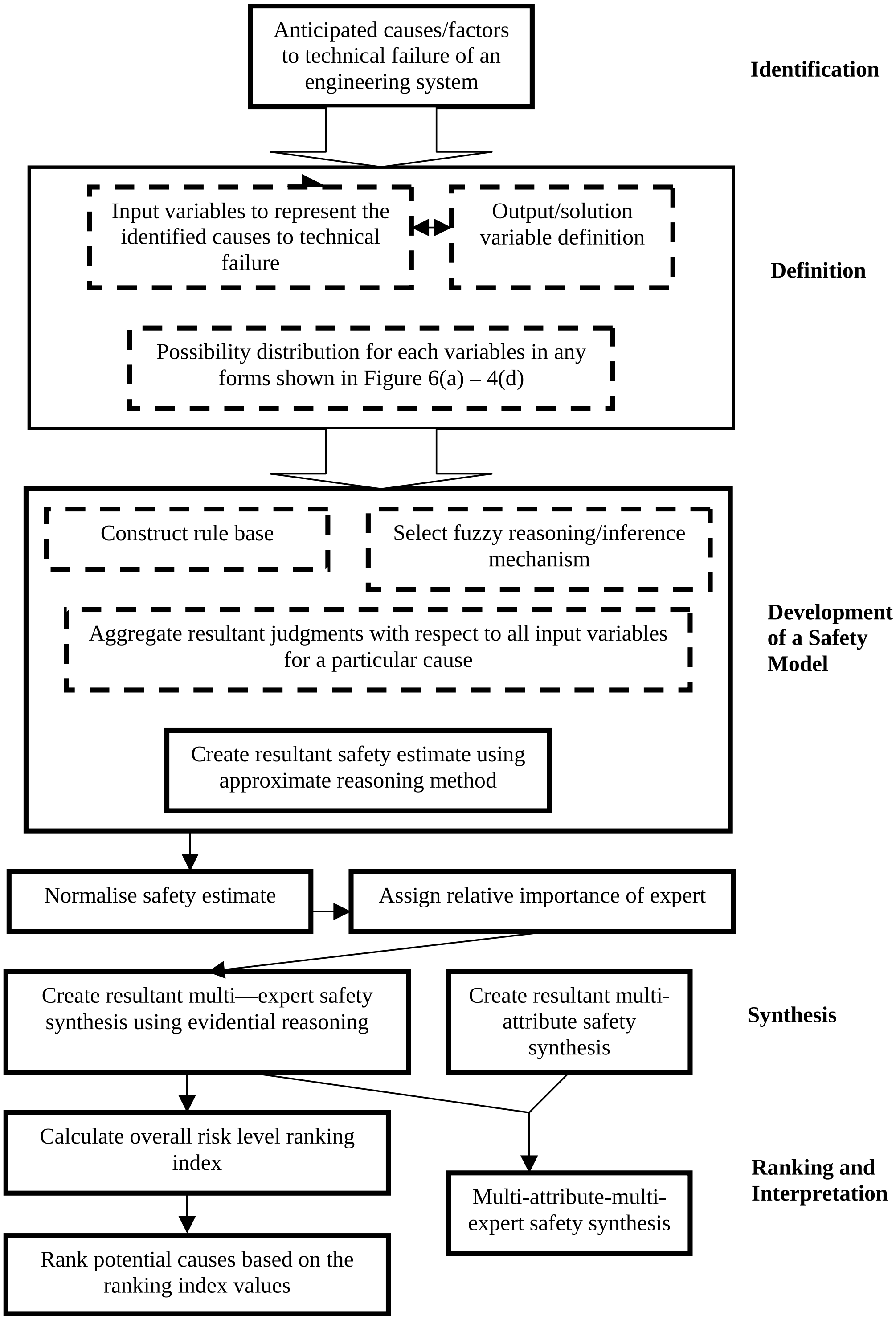

Figure 5: The process of modelling system safety using approximate reasoning and evidential reasoning approaches

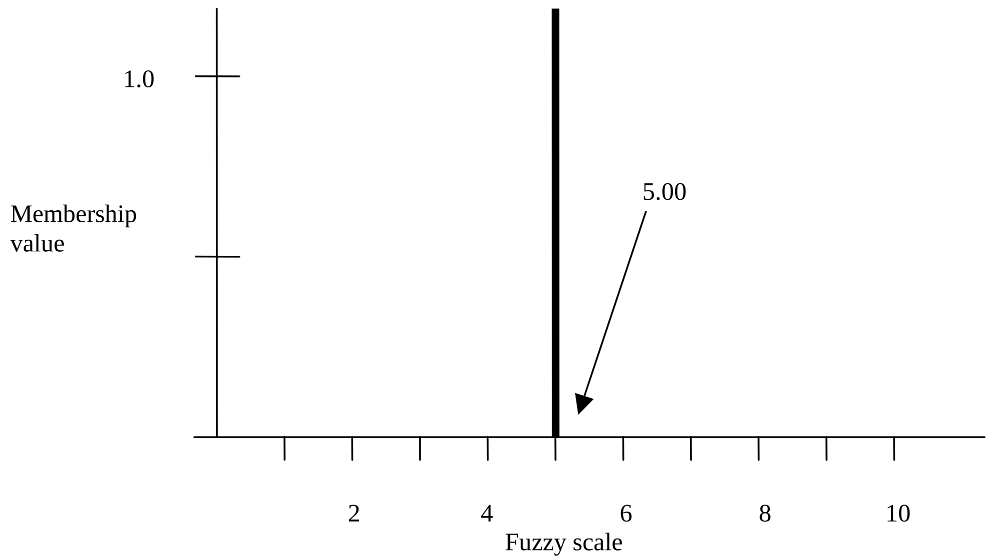

Figure 6 (a): A single deterministic value of 5.0 with 100 % certainty

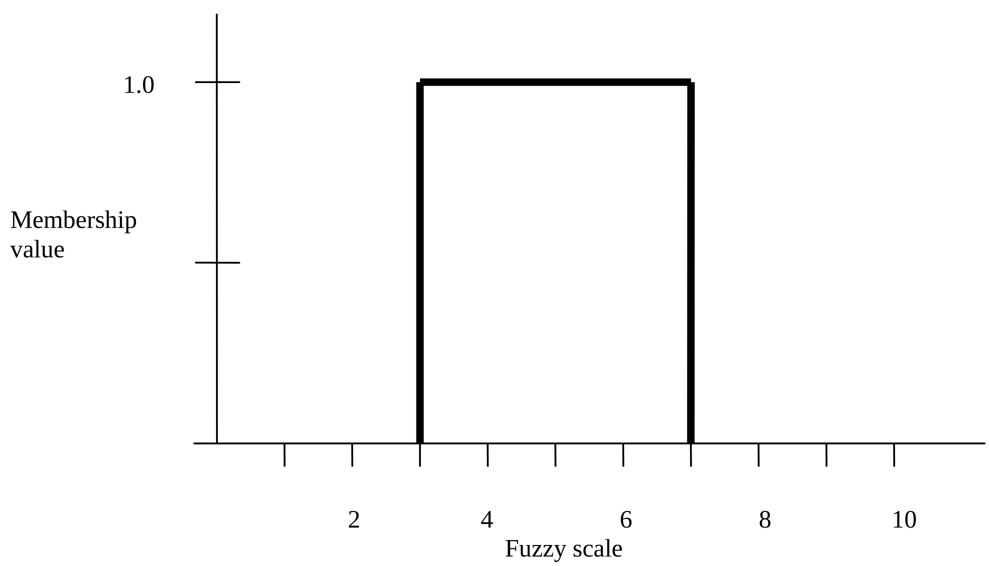

Figure 6 (b): A closed interval defined by an equally likely range between 3.0 and 7.0

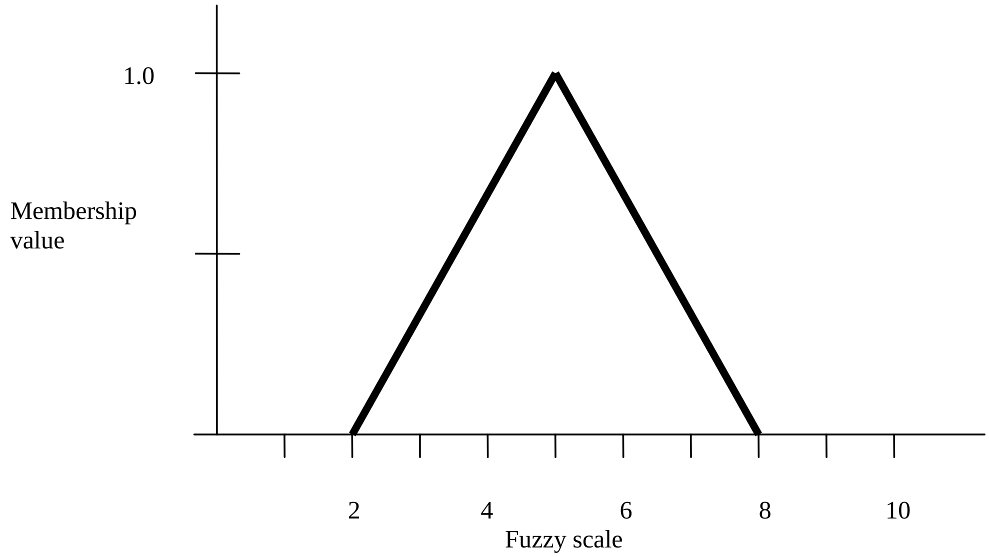

Figure 6 (c): A triangular distribution defined by a most likely value of 5.0, with a lower least likely value of 2.0 and an upper least likely value of 8.0

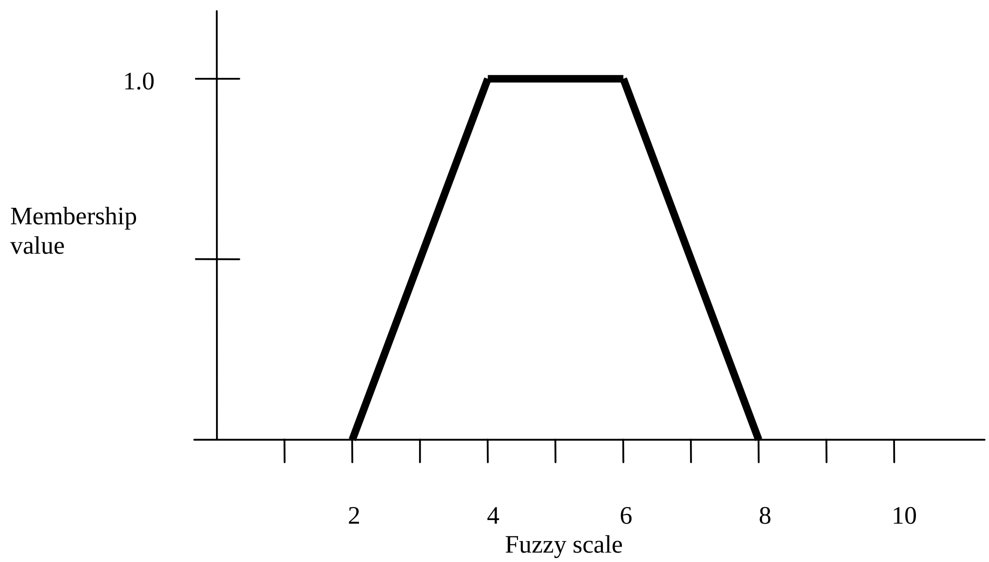

Figure 6 (d): A trapezoidal distribution defined by a most likely range between 4.0 and 6.0, with a lower least likely value of 2.0 and an upper least likely value of 8.0

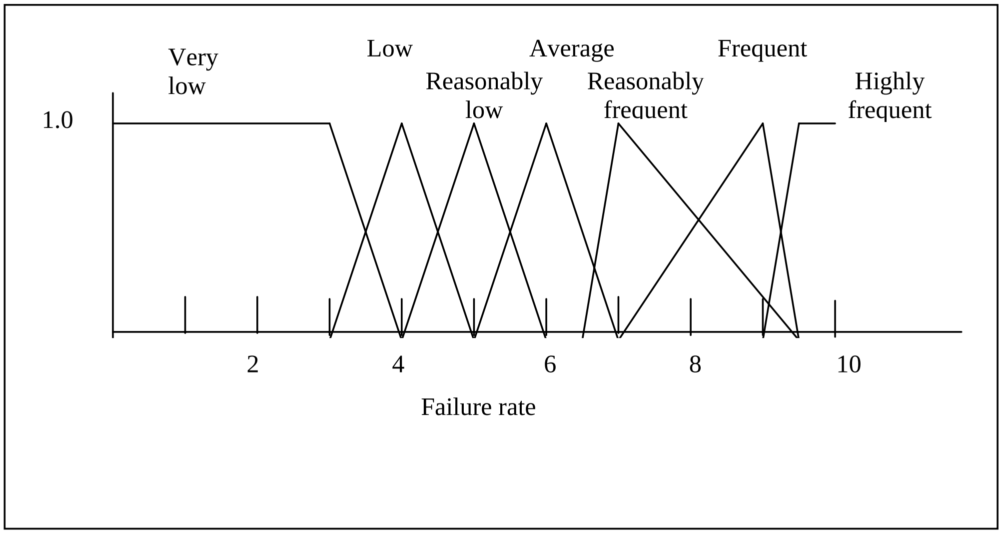

Figure 7: Fuzzy failure rate set definition

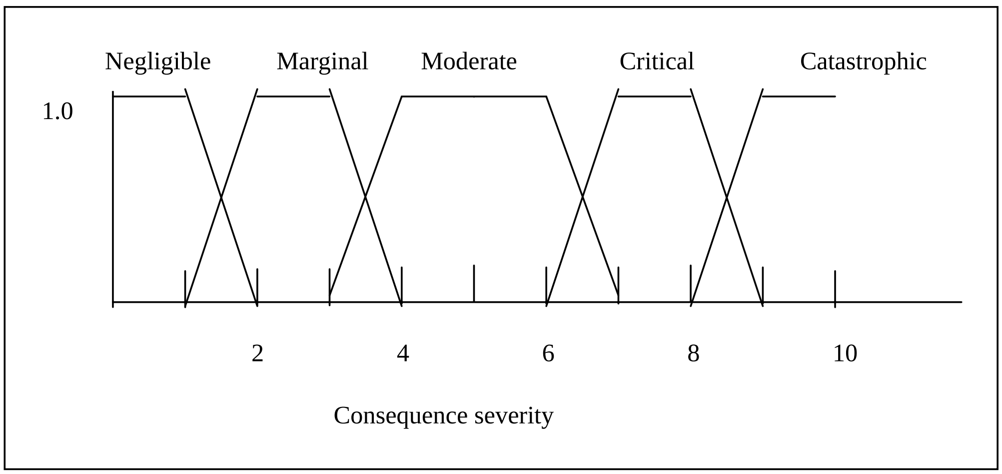

Figure 8: Fuzzy consequence severity set definition

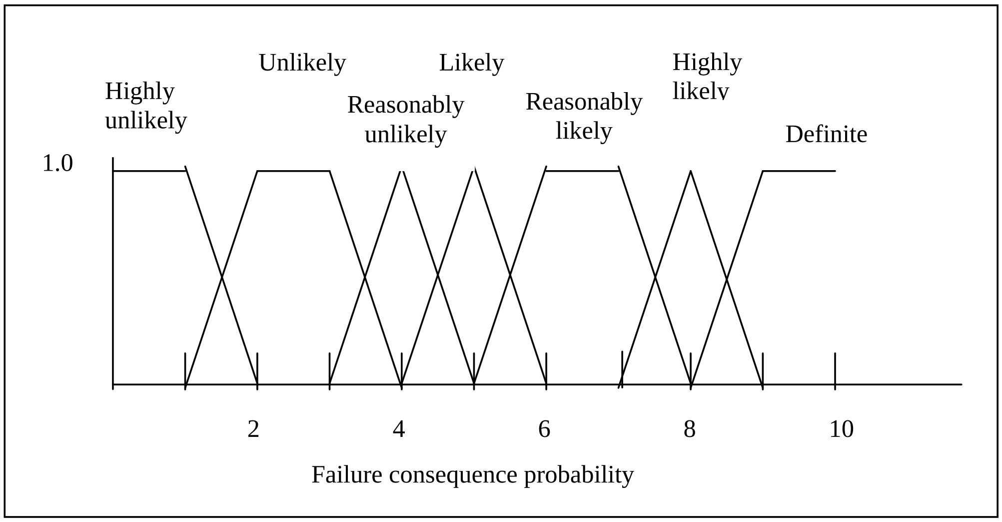

Figure 9: Fuzzy failure consequence probability set definition

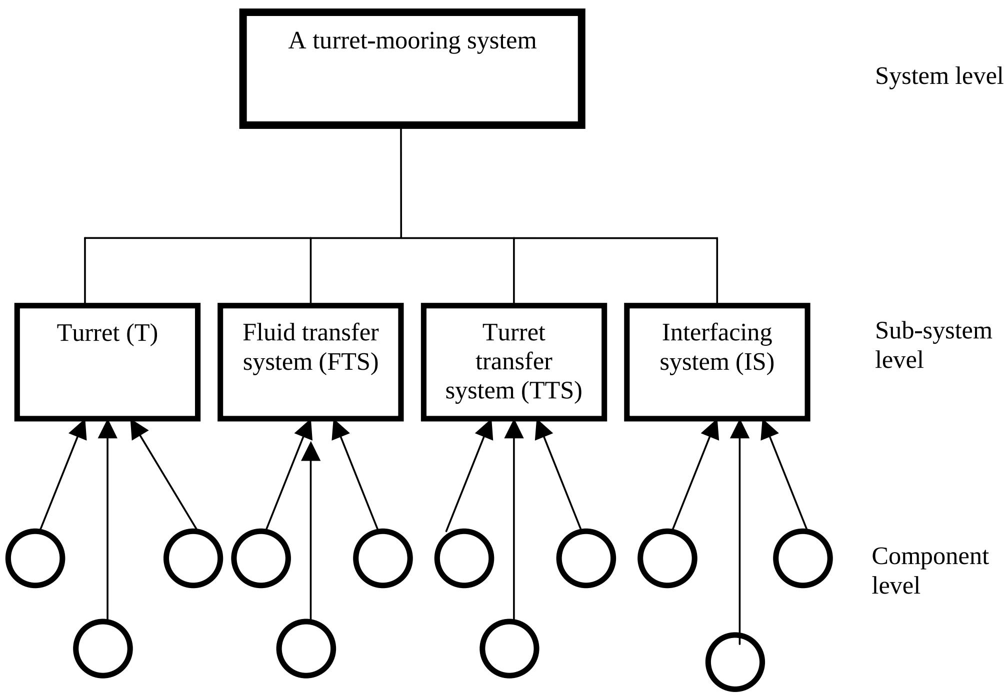

Figure 10: A generic hierarchical structure of a turret-mooring system

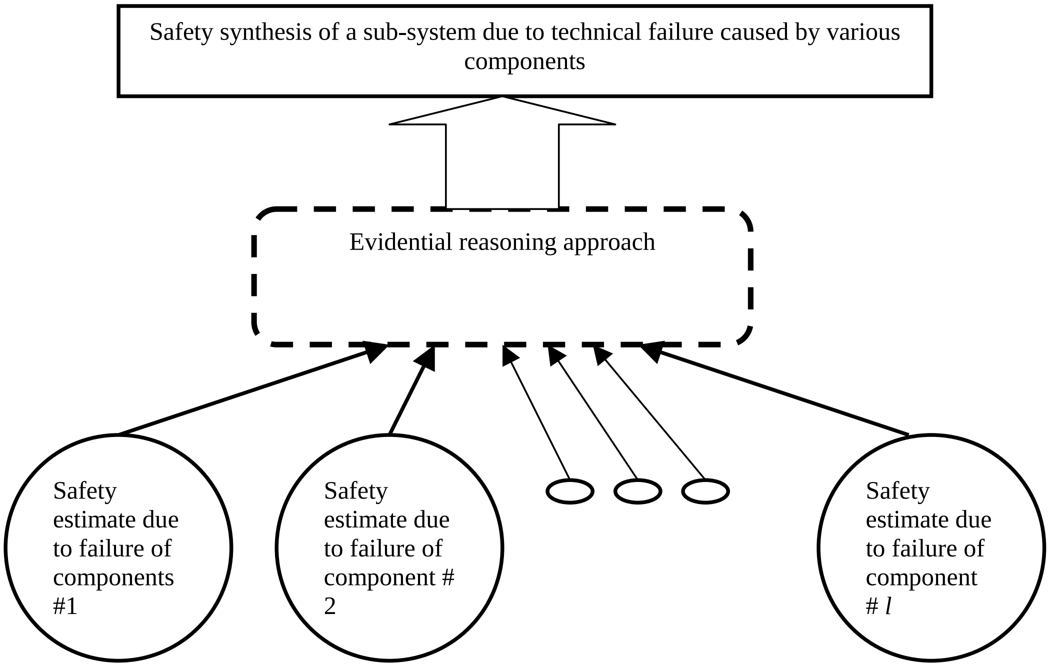

Figure 11: Multi-attribute safety synthesis of a sub-system due to technical failure caused by its constituent components using the evidential reasoning approach

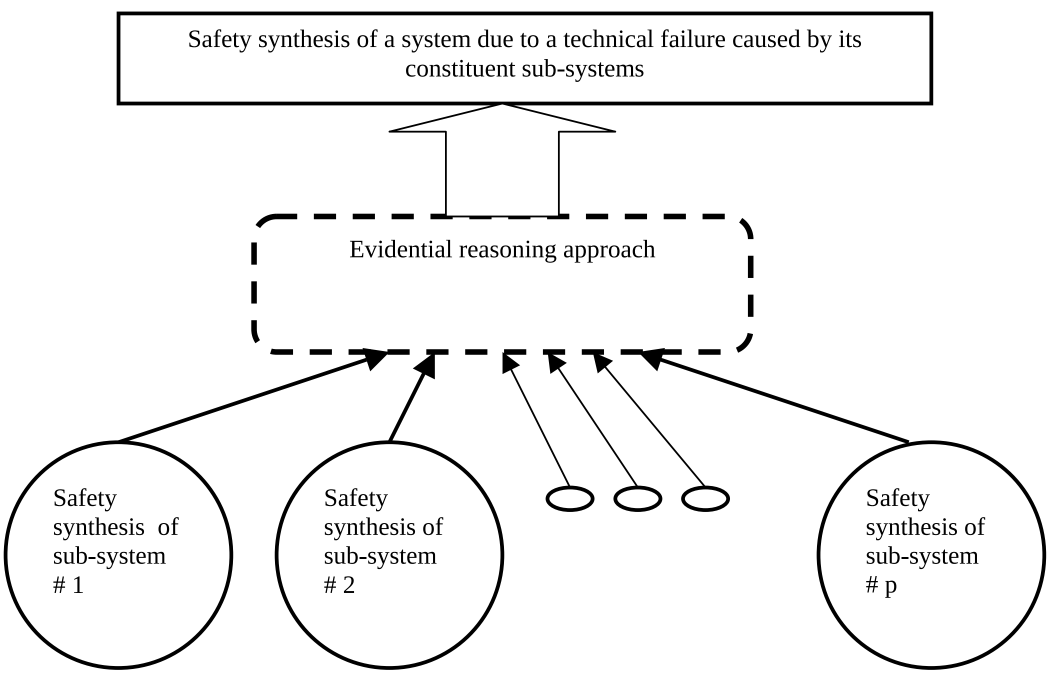

Figure 12: Safety synthesis of a system due to technical failure caused by its constituent sub-systems using the evidential reasoning approach