Human Error Assessment and Decision Making Using AHP Technique

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Abstract

A brief review of common human error assessment methods is presented highlighting the requirements and steps of each method. This is followed by an introduction to the Analytical Hierarchy Processing (AHP) method to aid decision-making. An approach to integrate human error assessment and decision-making using the AHP method is described. The aim of this approach is to reduce the occurrence probability and severity of human error during the operational phase of a fishing vessel. It utilises AHP theory to rank the impacts of human error and further integrates the available control options (to minimise these errors) within the analysis. The result obtained from the analysis reflects the most favoured control option that will address all the possible human errors within the system to a satisfactory level. A test case, which considers the shooting operation of a beam trawler, is used to demonstrate the described approach. Each step involved in the shooting operation is assessed for its vulnerability to human error with respect to the equipment being operated and this captures the operator-machine interaction.

Keywords: AHP, decision making, human error, human error assessment

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1.1Introduction

The cost of shipping casualties is normally expressed in terms of insurance values. The report of the Institute of London Underwriters (ILU) for 1995 stated that 95 ships were lost during the year (ILU (1996), ITSA (1996)). In 1996, the ILU recorded 1,190 lives lost at sea and the ship classification society Det Norske Veritas (DNV) estimated that accidents on board ships cost the industry around $US 10 billion a year (ILU (1996), IMO (1997)). It has been accepted that 80% of the accidents in the maritime industry is caused by human error. In the fishing industry, Lloyd's Register of World Fleet Statistics 1998 noted that the average age of the world fleet of fish catching vessels over 100 GRT was 20 years (ITWF (1999)). This could be a contributing factor to the high level of human error on these vessels. These older vessels lack automation and modern safety devices, hence the safe operation of the vessels is highly dependent on the competency of the crew on board.

Human error has played a critical role in the causes of many major marine accidents. The officers and crew of the *Herald of Free Enterprise* set to sea with their bow doors open (Sheen (1987)). The crew and skipper of the Pescalanza and Sapphire did not close their watertight doors during heavy seas, which led to the sinking of the vessels by flooding (MAIB (2000)).

In these accidents, life, cargo and property had been lost due to the negligence and/or mistakes made by the operators of the system. Understanding errors and system failures are particularly important with respect to "high-consequence" systems. These are open systems whose behaviour has a significant effect not only on the system itself but also on the world outside the system. Hence, there is a need for an effective method to model the risks posed by human error in order to direct the limited resources to solutions that would reduce these risks.

1.2 Review of Human Error Assessment Methods

Engineers have developed a range of tools that can be used to represent and reason about the causes of major accidents (Leveson (1995)). For example, time-lines and fault trees have been recommended as analysis tools by a range of government and regulatory bodies. Unfortunately, these well-established techniques suffer from a number of limitations (Johnson (1998)). In particular, they cannot easily be used to represent and reason about the ways in which human errors and system failures interact during complex accidents (Hollnagel (1993)).

1.2.1Methods for Quantification of Human Failures

Many methods for estimating human reliability were used in nuclear power plants. Such methods include confusion matrix (Fullwood and Hall (1988), Gertman and Blackman (1994)), expert estimation (Gertman and Blackman (1994)), Time Reliability Curve (TRC) (Dougherty and Fragola (1988), Moieni et al. (1994)), Maintenance Personnel Performance Simulation (MAPPS) (Fullwood and Hall

(1988), Gertman and Blackman (1994)), Success Likelihood Index Method-Multi-Attribute Utility Decomposition (SLIM-MAUD) (Fullwood and Hall (1988), Gertman and Blackman (1994)), sociotechnical assessment of human reliability (Gertman and Blackman (1994)), Technique for Human Error Rate Prediction (THERP) (Dhillon (1986)), Sandia Recovery Model (SRM), INTENT (Gertman et al. (1992)) and Operator Reliability Calculation and Assessment (ORCA). Of the methods given, most deal with misdiagnosis or non-response errors and time dependent probability estimates. The most commonly used techniques are THERP, utilising generic Human Error Probabilities (HEP) from various industries, and SLIM-MAUD, using importance weightings from experts.

1.2.2THERP

This method provides a mechanism for modelling as well as quantifying human error. It starts off with a task analysis that describes the tasks to be performed by the crew, maintainers or operators. Together with the task descriptions, Performance-Shaping Factors (PSF) such as stress and time available are collected to modify probabilities. The task analysis is then graphically represented in Human Reliability Assessment (HRA) event trees. The HEP for the activities of the task or the branches can be read and/or modified from the THERP tables as shown in (Gertman and Blackman (1994)). Details on the construction of HRA event trees and also the COGnitive EveNt Tree (COGENT) to represent cognitive activities and errors associated with human performance are also given in the book. Gertman and Blackman also provided a summary of the steps to THERP, which was adapted from the Nuclear Regulation-NUREG/CR-1278 (Swain and Guttmann (1983)). THERP may suffer from the following limitations (Reason (1990), White (1995)):

1. It is difficult to represent the variability of human behaviour adequately.
2. The technique assumes that each task segment can be handled separately.
3. It is difficult to combine human and equipment reliability values.
4. It is difficult to identify inter-task dependencies.
5. The technique is not appropriate for continuous tasks.
6. The method does not determine motivation of the individual.
7. Analysts have the tendency to model only errors that appear in databases.

1.2.3 Accident Sequence Evaluation Programme (ASEP)

ASEP is a quicker version of THERP and is more conservative. It is a fine screening approach and can be complemented with THERP to warrant more detailed attention in the risk assessment. A more detailed discussion on ASEP can be found in (Swain (1987)).

1.2.4 SLIM-MAUD

The SLIM-MAUD method is centred on the assumption that the failure probability associated with task performance is based on a combination of PSFs that include the characteristics of the individual, the environment, and the task. It further assumes that experts can estimate these failure rates or provide anchor values to estimate them. A description on the steps to perform SLIM-MAUD was reported in (Gertman and Blackman (1994)) where two enhanced methods were developed. Dougherty and Fragola also provided the mathematics and an example for calculating SLIM-MAUD (Dougherty and Fragola (1988)). Davoudian et al provided an empirical evaluation of SLIM-MAUD and ranking to estimate HEPs, through the use of a simulated manufacturing environment under varying task conditions (Davoudian et al. (1994)).

1.2.5 Human Reliability Assessment (HRA)

HRA analyses the relationship between human behavioural tendencies and the work context to provide a better understanding in anticipating human errors, violations and severe system outcomes. This analysis requires a fundamental understanding of:

1. The way humans process information, including their capabilities and limitations at such processing (Wickens (1992)).
2. Human factors and ergonomics design consideration (Sanders and McCormick (1987)).
3. Skill, rule and knowledge based framework, which describes distinct levels of information processing at which workers perform (Rasmussen (1982, 1986)).
4. Psychosocial considerations that increase the likelihood of performing violations (CCPS (1994)).

The primary goals of HRA are to assess the risks attributable to human error and determine the ways of reducing system vulnerability due to human error impact. These goals are achieved by its three principal functions of identifying what errors can occur (human error identification), deciding how likely the errors are to occur (human error quantification), and, if appropriate, enhancing human reliability by reducing this error likelihood (human error reduction). The HRA process can be broken down into several steps as seen below:

Problem definition: This refers to deciding what human involvements are to be assessed (operators failing to deal with emergencies, operator's contribution to maintenance failures, etc.)

Task analysis: When the human aspect of the problem has been defined, task analysis can then define what human actions should occur in such events, as well as what equipment and other "interfaces" the operator should use. It may also identify what training (skills and knowledge) and procedures the operators will call upon.

Human Error Identification (HEI): Once the task analysis has been carried out, HEI then considers what can go wrong. The following types of errors are typically considered:

1. Error of omission - failing to carry out a required act.
2. Error of commission - failing to carry out a required act adequately; act performed without required precision, or with too much or too little force; act performed at wrong time; act performed in the wrong sequence.
3. Extraneous act - not required act performed instead of, or in addition to the required act.
4. Error-recovery opportunities - acts which can recover previous errors.

The HEI phase can identify many errors. Not all of these will be important for the study, as can be determined by reviewing their consequences on the system's performance. The ones that can contribute to a degraded system state, whether alone or in conjunction with other hardware/software failures or environmental events (or both together), must next be integrated into the risk analysis.

Representation: Having defined what the operator should do (via task analysis) and what can go wrong, the next step is to represent this information in a form which allows the quantitative evaluation of the human-error impact on the system to take place. It is usual for the human error impact to be seen in the context of other potential contributions to system risk. Human errors and recoveries are usually embedded within logical frameworks such as fault tree analysis and event tree analysis.

Human error quantification: Once the human error potential has been represented, the next step is to quantify the likelihood of the errors involved and then determine the overall effect of human error on the system safety and reliability. HEP is simply defined as "number of errors that occurred/number of opportunities for error".

Impact assessment: Once the errors have been quantified and represented in the risk assessment logic trees, the overall system risk level can be calculated. Then it can be determined whether or not the system has an acceptable level of risk. Impact assessments involve determining if the risk element is acceptable as well as which events (human, hardware, software or environmental - or any combination) contribute most to the level of risk. If the human error is a significant contributor to the overall risk at the system level, and if the system risk level is calculated to be too high, then the appropriate error will be targeted for reduction.

Error reduction analysis: Error reduction measures may be derived:

- According to the identified root causes of the error (from the error identification stage).
- From the defined factors that contribute to the HEP.

If error reduction is necessary to reduce the risk to an acceptable level, then following such error reduction measures, several iteration of impact assessments, error reduction and re-quantification may occur until satisfactory risk levels are achieved.

1.3Human Error Probability

The analysis of many accidents has led to the appreciation that multiple equipment failures and process deviations combined with faulty human decisions and actions are often involved. Safety assessments, therefore, are not complete unless the interactions between equipment failures and human actions are considered. Since human behaviour is complex, and does not lend itself immediately to relatively straightforward reliability models, it is suggested that the following classifications of human interactions (that typically group all activities) need to be considered (Mahn et al. (1995)):

- Pre-initiator human interactions involving maintenance, testing, calibration, planning, etc.
- Initiators of accidents that involve operator awareness of potential accident initiators caused by errors in tests, or reconfiguration conditions involving control systems, protective logic, computer controlled functions and manual control.
- Post initiator interactions that involve procedure specified actions and recovery actions developed from training and experience.

These classifications of human interactions can be related to a simple error classification system consisting of three categories: (1) slips, (2) non-response, and (3) mistakes. This classification scheme can then be used to qualitatively incorporate human errors in accident scenarios. Table 1.1 provides generic human error probabilities for use in accident scenario assessment (Department of Energy (1996)).

The development of a generic set of human error probabilities is extremely difficult since there is a strong correlation on the actual person performing the task, the complexity of the task, the time required for task completion, and the training level of the person performing the task. Additionally, a worker may perform any specific task differently depending on the level of alertness due to fatigue or other factors.

A relatively simple model has been developed by Rasmussen to quantify human error rates based on the level of training (Rasmussen (1979, 1981)). This model divides the behaviour into three basic categories: skill-based, rule-based, and knowledge-based behaviours.

1.3.1 Skill-Based

Skill-based behaviours depend mostly on the operator's practice in performing the task. In short the operator can perform the task without ambiguity. A simplistic view is that skill-based errors are slips or lapses. These errors tend to be related to highly routine activities in familiar circumstances: omissions, repetitions, reversals, interference errors and double-capture slips. An example is incorrect use of foot pedal controls of fork-lift trucks. Some fork-lift trucks operate with three pedals (as a car), others have two pedals, reverse and forward. Removing a foot from either accelerator brings the vehicle to a halt. A common error is for the driver to press the backward accelerator in the belief (wrongly) that it is a brake pedal. Examples of slips and lapses include:

- Failing to disengage the gears before starting the engine (omission).
- Turning the ignition key to start the engine, when the engine is already running (repetition).
- Pressing the brake instead of the accelerator (reversal).

1.3.2 Rule-Based

Rule-based behaviour is at work when the operator does not have the same level of practice at performing the required task, but has a clear knowledge of the procedures. There may be some hesitation in recalling any procedure, the procedure may not be carried out in the proper sequence, or any step may not be performed precisely.

Rule-based errors are concerned with the misapplication or inappropriate use of problem solving rules. Individuals have a complex array of specific and general rules that they use to deal with everyday problems. Rules are of the type *if* <event>*then* <action>. Some simplistic examples relating to the operation of vehicles are:

• *if* <machine blockage>*then* <disengage power, switch off engine and investigate>
• *if* <pallet insecure>*then* <re-secure>
• *if* <towing a trailer on slopes>*then* <connect trailer brakes>
Sometimes the operator's rules are incomplete:
• *if* <emergency>*then* <apply handbrake, switch off engine, and dismount>

This is a perfectly good rule under most circumstances. However, with accidents involving contact with high voltage overhead lines, remaining in the cab provides protection against electrocution (principle of the Faraday Cage). A better additional rule would be:

• *if* <emergency involving electricity>*then* <stay in cab until supply isolated>.
The role of training in providing individuals with a set of safe rules is crucial.

1.3.3 Knowledge-Based

Knowledge-based action would include situations where the operator needs to contemplate the situation, interpret information or make a difficult decision. Also included in this grouping would be cases where a procedure is not well spelled out. In these cases the person performing the task must consider the actions to be taken and not act according to specific training.

Knowledge-based errors are concerned with performance in novel or new situations. Actions have to be planned "on-line" and the process is intellectually demanding. The problem solver will only resort to this type of activity when he has run out of rule-based solutions. An example of knowledge-based performance is that of first learning to operate a piece of machinery. The hydraulic controls of a winch provide a good example. Experimentation will help the operator to build a mental model of how the controls can be co-ordinated to achieve the desired movements. Eventually, the operator will adopt a set of rules derived from that mental model. With practice, the task will become skill-based. Training offers the opportunity to miss out the experimentation phase by guiding the trainee to a correct model of situations, based on the experiences of others.

Rasmussen provided per demand ranges and point estimates for these different categories (Rasmussen (1982)). These values are presented in Table 1.2. Swain and Guttmann suggested for screening purposes, the values of 0.05 and 1 are used for the rule-based and knowledge-based actions, respectively (Swain and Guttmann (1983)). However a value of 1 means 100% error rate for the knowledge-based action, a value that would appear to be unrealistically high.

One problem with the Rasmussen data is that it requires subjective analysis of the operator's training and capabilities. A set of human error rates was developed by Hunns for more specific tasks, not relying as much on the operator's capabilities and knowledge (Hunns (1982)). These data are presented in Table 1.3 and were based on extrapolation from human error rate databases. These data are similar to the rates of Rasmussen in Table 1.2 but provide some actual examples and do not require as much subjective analysis as the Rasmussen data.

The human error rates for some specific tasks have been provided by Dhillon and are presented in Table 1.4 (Dhillon (1986)). Dhillon points out that there are six basic categories of error sources that can eventually lead to an accident condition:

1. Operating errors
2. Assembly errors
3. Design errors
4. Inspection errors
5. Installation errors
6. Maintenance errors

Operating errors can be the result of:

1. Lack of proper procedures.
2. Task complexity and overload (of operator) conditions.
3. Poor personnel selection and training.
4. Operator carelessness and lack of interest.
5. Poor environmental conditions.
6. Departure from following correct operating procedures.

1.4 Analytical Hierarchy Processing

Analytical Hierarchy Processing (AHP) is a powerful and flexible decision making process to help set priorities and make the best decision when both qualitative and quantitative aspects of a decision need to be considered. By reducing complex

decisions to a series of one-on-one comparisons, then synthesising the results, AHP not only helps decision-makers arrive at the best decision, but also provides a clear rationale that it is the best. Designed to reflect the way people actually think, AHP was developed more than 20 years ago by Dr. Thomas Saaty (Saaty (1980)), and continues to be the most highly regarded and widely used decision-making theory.
AHP is especially suitable for complex decisions, which involve the comparison of decision elements that are difficult to quantify. It is based on the assumption that when faced with a complex decision the natural human reaction is to cluster the decision elements according to their common characteristics. It involves building a hierarchy (ranking) of decision elements and then making comparisons between each possible pair in each cluster (as a matrix). This gives a weighting for each element within a cluster (or level of the hierarchy).
The AHP engages decision-makers in breaking down a decision into smaller parts, proceeding from the goal to criteria to sub-criteria down to the alternative courses of action. Decision-makers then make simple pair-wise comparison judgements throughout the hierarchy to arrive at overall priorities for the alternatives.
The literature survey on AHP indicates that the method has been effective to a wide range of applications. These include agricultural applications (Alho and Kangas (1997), Braunschweig (2000)), industrial engineering applications (Alidi (1996), Bhattarai and Fujiwara (1997)) and financial applications (Hachadorian (1987), Gerrits et al. (1994)). The application of AHP theory to ascertain business and financial risk has been relatively popular in the past (Jensen (1987a, b), Nezhad (1988), Simkin et al. (1990)). It has also found its place in risk and safety assessment of engineering systems (Shields and Silcock (1986), Saaty (1987), Hamalainen and Karjalainen (1989), Shields et al. (1990), Hamalainen and Karjalainen (1992), Frank (1995).

1.4.1 Principles and Background of AHP

When considering a group of activities (factors) for evaluation, the main objectives of this group are (Saaty (1990)):

1. To provide judgement on the relative importance of these activities.
2. To ensure that the judgements are quantified to an extent which also permits a quantitative interpretation of the judgement among these activities (factors).

The quantified judgements on pairs of activities C_i and C_j are represented by an n-by-n matrix.

$A = (a_{ij})$ where $i, j = 1, 2, \ldots, n$. (1.1)

The entries a_{ij} are defined by the following entry rules:

Rule 1. If $a_{ij} = \alpha$, then $a_{ji} = 1/\alpha$, $\alpha \neq 0$.

Rule 2. If C_i is judged to be of equal relative importance as C_j, then $a_{ij} = a_{ji} = 1$. Obviously $a_{ii} = 1$ for all i. Thus the matrix A has the following form:

(1.2) $$A = \begin{bmatrix} 1 & a_{12} & ..... & a_{1n} \\ 1/a_{12} & 1 & ..... & a_{2n} \\ . & . & ..... & . \\ 1/a_{1n} & 1/a_{2n} & ..... & 1 \end{bmatrix}$$

where each $a_{ij}$is the relative importance of activity i to activity j. Having recorded the quantified judgements of comparisons on pair (C_i, C_j) as numerical entry a_{ij}in the matrix A, what is left is to assign to the n contingencies C_1 , C_2 , C_3 , ..., C_na set of numerical weights $w_1, w_2, w_3, ..., w_n$ that should reflect the recorded judgements. The eigenvector of the comparison matrix provides the priority ordering (weight), and the eigenvalue is a measure of consistency. To find the priority vector or the weight of each factor included in the priority ranking analysis, the eigenvector corresponding to the maximum eigenvalue is to be determined from matrix analysis. One of the approximation methods to get the weight of each factor in the pair-wise comparison process is described below.

1.4.2 Weight Vector Calculation

In mathematical terms, the principal eigenvector is computed, and when normalised becomes the vector of priorities (weights). To reduce the excessive computing time needed to solve the problem exactly, and due to the results of complex numbers, a good estimate of that vector can be obtained by dividing the elements of each column in the comparison matrix by the sum of that column (i.e. normalise the column). The elements in each resulting row are added and the sum is divided by the number of the elements in the row. This is a process of averaging over the normalised columns. Mathematically, the equation for calculating $w_1$is shown below:

(1.3) $$w_1 = \frac{1}{n}\left[\left(\frac{a_{11}}{\sum_{i=1}^{n} a_{i1}}\right) + \left(\frac{a_{12}}{\sum_{i=1}^{n} a_{i2}}\right) + ...\left(\frac{a_{1n}}{\sum_{i=1}^{n} a_{in}}\right)\right]$$

In general, weights $w_1, w_2, w_3, ..., w_n$ can be calculated using the following equation:

(1.4) $$w_k = \frac{1}{n}\sum_{j=1}^{n}\left(\frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}}\right) \ (k = 1, ……n)$$

where $a_{ij}$is the entry of row i and column j in a comparison matrix of order n.

1.4.3 Risk and AHP

Risks are by nature subjective, therefore, the AHP method may be suited for risk assessment in many situations. This technique allows subjective and objective factors to be considered in risk analysis and also provides a flexible and easily understood way to annualise subjective risk factors. The elements in each level are compared pair-wise with respect to their importance in making the decision under consideration. The verbal scale used in AHP enables the decision-maker to incorporate subjectivity, experience and knowledge in an intuitive and natural way.

After the comparison matrices have been created, the process moves on to the phase in which relative weights are derived for the various elements. The relative weights of the elements of each level with respect to an element in the adjacent upper level are computed as the components of the normalised eigenvector associated with the largest eigenvalue of their comparison matrix. The composite weights of the decision alternatives are then determined by aggregating the weights through the hierarchy. This is done by following a path from the top of the hierarchy to each alternative at the lowest level, and multiplying the weights along each segment of the path. The outcome of this aggregation is a normalised vector of the overall weights of the options. The mathematical basis for determining the weights has been established by Saaty (Saaty (1980)).

1.4.4 AHP for Human Error Assessment and Decision Making for Ship Operations

Several methods to quantify human error probability have been reviewed in Section 1.2. These methods suffer from the difficulty associated with any attempt to construct quantitative, predictive models of human behaviour. The qualitative methods on the other hand, require multi-disciplinary teams to carry out an analysis and this is regarded as being resource intensive. The more recent HRA methods have included cognitive aspects of decision making and the "time" dimension. However, it has not yet captured the fundamental nature of the interaction between actions and machine responses (Cacciabue et al. (1993)). These interactions lie in the mutual dynamic influence of the operator, the plant and the interfaces.

The use of AHP to evaluate human error on ship operations does not ignore small events or operations that are normally rationalised and eliminated as being not important in traditional methods. A chain of these small rationalisations results in a larger problem later. The AHP method looks at every event/operation and ranks them against each other to determine the importance of each event/operation over the other (without eliminating them from the analysis).

The use of the AHP method enables the solutions for each possible human error identified, to be integrated within the analysis. This is unlike the methods reviewed in Section 1.2, where the solutions to reduce the risk levels (posed by human errors) are evaluated in the first instance, and then a re-iteration of the whole analysis is performed (assuming the implementation of the solution) to confirm the risk reduction. An approach using the AHP method for human error assessment and decision making applied to ship operations is presented in Section 1.5.

1.5 Application of AHP to Vessel Operations

The flowchart in Figure 1.1 illustrates the steps involved in carrying out the application of AHP to vessel operations (Pillay (2001), Pillay and Wang (2001)). This approach can be executed in the following seven distinct steps:

1. Describe system - The system or operation under consideration is described in detail, highlighting all the equipment within the system that will be operated to achieve the desired objective of the defined operation.
2. Identify tasks to be carried out - Identify all tasks that are to be carried out to achieve the objective of the operation and present these tasks in the order that they should be carried out. This information can be represented by means of a flowchart. The order by which the tasks are carried out should reflect the normal safe working procedure of the system. To enable effective use of this information in the AHP phase, all tasks are annotated according to the equipment that are operated.
3. Determine operator behaviour - For each of the tasks identified in Step 2, determine the required operator’s behaviours. Three types of behaviours are considered namely, skill-based, rule-based or knowledge-based behaviour. These behaviours are discussed in Sections 1.3.
4. Determine the probability of occurrence - Using a generic database, determine the probability that a human error might occur while carrying out the task specified in Step 2. Use the information developed in Step 3 to assign the probability of occurrence of the human error.
5. Determine the severity of occurrence - The severity of a human error should take into account the consequences of the error on the system, operation, environment and operator. This can be quantified in monetary terms or downtime.
6. Determine Risk Control Options (RCOs) - Considering the system/operation under study, determine several options that could address the risks estimated (associated with each task defined in Step 2).
7. AHP analysis - Using the data gathered in Steps 2, 4, 5 and 6, carry out the AHP analysis to determine the most favourable RCO. This RCO will address all the risks associated with tasks where human errors could manifest.

Step 7 (AHP analysis) involves 4 distinct steps, which are described below:

(a) Set-up - Decision making criteria are generated, often by brainstorming or past experience. Hierarchical relationships are drawn between the criteria and are then represented in a matrix form.

(b) Weighting - The matrices are filled with the criteria comparisons. The comparisons allow calculation of the criteria-weighting vector.

(c) Ranking - The different RCOs are ranked on their ability to satisfy the various criteria.

(d) Evaluation - The final solution ratings are then calculated using the ratings determined in step (c) and the weighting vector calculated in step (b).

The first task is to decide on the problem statement. This statement becomes the goal of the hierarchy (Level One) and will be broken down into nested levels (Level Two). Level Two will comprise the different elements needed to be considered to achieve the goal set in the problem statement. The elements in Level Two are further broken-down to represent the various constituents that make up or belong to each specific element. The hierarchical structure is assumed to exist inherently in the problem considered and can be identified.

The hierarchy records the flow of detail from the problem statement (Goal) to broad issues (Level Two) and more specific levels (Level Three). While the concerns on a particular level are not equally important, they should be on the same order of magnitude. This feature in AHP allows decisions to be made involving different orders of magnitude criteria, by placing each criterion in its proper matrix in the objective hierarchy. Figure 1.2 shows an example of the hierarchy represented diagrammatically.

Once the hierarchy has been completed, matrices are constructed with the criteria labels on each axis. There will be one Level Two matrix and a number of associated matrices for the sub-elements of each element. For example, Figure 1.2 will have one Level Two matrix and three Level Three matrices. These Level Three matrices may be broken down in finer detail where applicable. The two axes of a matrix will contain the names of the elements on the level being considered. For example, the Level Two matrix in Figure 1.2 will have the form shown in Table 1.5. The elements below Level Two would also be represented in a matrix form. Table 1.6 shows an example for Element 1 (constituent *A*) matrix. The complete representation of Element 1 would comprise three matrices (as Element 1 has the constituents *A, B* and *C*).

As the described method does not use historical data (probability of occurrence in terms of hard numbers or severity in terms of number of deaths), the uncertainty in these parameters is captured by representing them in terms of preference/importance against each other. Hence, the analysis is targeted at improving the current situation by identifying the areas that need improving, rather than trying to quantify the occurrence likelihood/severity of an undesired event.

Upon generating the matrices for all the elements, it must now be filled with the comparisons of the relative importance of the elements on the two axes. The comparisons are used to calculate the weighting vector that will give the relative importance of all the elements. The entire weighting vector is calculated from comparisons made between just two elements at a time. Table 1.7 shows the scale (1 to 9) proposed by (Saaty (1980)) for indicating the relative importance between the elements.

Considering the example of the Level Two matrix in Table 1.5, and assuming that Element 1 is weakly more important than Element 2 and strongly more important than Element 3. Then, the matrix in Table 1.5 may be represented as seen in the matrix below:

$$Level\ Two = \begin{bmatrix} 1 & 3 & 7 \\ 1/3 & 1 & 7/3 \\ 1/7 & 3/7 & 1 \end{bmatrix}$$

In the matrix, Element 1 is of equal importance with respect to itself, so 1 is placed in the upper left-hand corner. A consistent matrix formulation allows the remainder of the matrix to be completed given the information in the top row. Since the relationship is known between Element 1 and Element 2, and Element 1 and Element 3, the relationship between Element 2 and Element 3 can be determined. In this case the matrix entry for Element 2 versus Element 3 would contain 7/3.

The weighting vector is then determined to give the percentage of the total weight applied to each element. The first column in the Level Two matrix, (1, 1/3, 1/7) is normalised so that the sum of the entries is 1.0. The weighting of Element 1 will be given as 1/(1+1/3+1/7) = 0.677 or 67.7%. Similarly Elements 2 and 3 can be calculated to be 22.6% and 9.78%. The normalised weighting vector for Elements 1, 2 and 3 is $[0.667\ 0.226\ 0.097]^T$. The sum of all three weightings is equal to 100%.

The comparison process is repeated for all the matrices to be used in the analysis. The weighting vectors of the lower matrices will be normalised so that their total weight will equal that of the previous level (Level Two). For example, for Element 1, sub-elements A_1, A_2, A_3, B_1, B_2, C_1, $C_2$and C_3 will be given a total weight of 67.7%. All sub-elements are analysed in the same fashion to the lowest level possible and the results are normalised to reflect the weight of each sub-element in the hierarchy.

The next step is to generate the possible solutions to achieve the problem statement/goal. Each solution is compared against each of the lowest level sub-elements. The possible solutions are assumed to reduce the likelihood of human error occurring and/or the possible consequences. The evaluation represents the "effectiveness" of the solution in controlling the risks. These evaluations (of the solutions) are recorded with a user defined numerical scale, as appropriate for the sub-elements. For any given element, a normalised score is determined for each solution by taking the assigned score (which may have units) and dividing it by the sum of the assigned scores across all of the solutions. This fraction is then multiplied by the weighting coefficient for the element. This will give a normalised score for each solution based on the element considered. These normalised results are then summed for the different elements in the matrix, to arrive at a final rating for each solution. The result of this series of operations is a weighted rating for each solution. The highest rated solution will best meet the problem statement (goal).

1.8 References (Chapter 9)

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Table 1.1 Generic Human Failure Probabilities

Human Error Probability	Description of human interaction and error	Example factors for a facility specific adjustment
3×10^{-3} to 3×10^{-4}	Pre-Initiator actions - test, maintenance, and calibrations leaving a component, or system with un-revealed fault. Include typical errors in maintenance that cause overall system unavailability (10^{-3})	No written procedure available, or newly defined action; verbal instructions, no checking for completed action, poor equipment/procedure identification label matching.
	Errors include: slips, non-responses, or mistakes leading to skipping a procedure, selecting an incorrect procedure, omitting a step in a procedure, improper communication, transposition of labelling, or misunderstanding task responsibility.	Use established, practised, written procedures, discussed in training, work progress verified with signed checklist, apply self-checking, use tag-out system to maintain configuration control, etc.
1×10^{-2} to 1×10^{-4}	Initiator actions - test, maintenance and calibration activities that trigger events. Include contribution of errors that cause initiating events - covered in initiating event frequencies (10^{-3})	Signals and instruments inappropriate for the action and procedure, lack of cues, or verbal instructions for interlocks, need for process knowledge, requires interpretation of indirect information, etc.
	Typical error modes include slips, non-responses and mistakes.	Indications permit easy transfer through procedures, discussed in training, practiced before hand, administrative control of tags, training involves understanding of the basic principles, and feedback of lessons learned from event precursors.
l to 1×10^{-3}	Post-Initiator actions - response actions that are not successful in terminating or mitigating the event. Include recovery actions subsequent to initiating events: (1) following multiple failures and (2) directly following an initiating event.	Actions typically outside control room, involves more than one person, lack of a clear cue, knowledge of the process required, process knowledge substituted for emergency procedures, etc.

	Errors include slips, mistakes, and non-responses for control and mitigation actions following an initiating event.	Actions in a control room, include redundant cues, memorised and practised responses, clear man-machine interface, action priorities stressed in training which includes simulation of process dynamics, recoverability from errors, training on infield procedures and long time available for action.

Table 1.2 Error Rates of Rasmussen

	Per demand error rate range	**Per demand error rate point estimate**
Skill-based	5E-5 to 5E-3	1E-3
Rule-based	5E-4 to 5E-2	1E-2
Knowledge-based	5E-3 to 5E-1	lE-1

Table 1.3 Error Rates of Hunns

Classification of error type	**Typical probability**
Processes involving creative thinking, unfamiliar operations where time is short; high stress situations	0.1-1
Errors of omission where dependence is placed on situation cues or memory	1E-2
Errors of commission such as operating wrong button, reading wrong dial, etc.	1E-3
Errors in regularly performed, common-place tasks	1E-4
Extraordinary errors - of the type difficult to conceive how they could occur; stress-free, powerful cues militating for success	<1E-5

Table 1.4 Error Rates of Dhillon

Error	**Rate per demand**	**Rate per plant-month**
Reading a chart recorder	6E-3	
Reading an analogue meter	3E-3	
Reading graphs	1E-2	
Interpreting incorrectly an indicator	1E-3	
Turning a control in the wrong direction under high stress	0.5	
Using a checklist incorrectly	0.5	
Mating a connector	1E-2	
Choosing an incorrect panel control out of several similar controls	3E-3	
Reading a gauge incorrectly	5.0E-3	
Closing a valve improperly	1.8E-3	
Soldering connectors improperly	6.5E-3	
Actuating switch inappropriately	1.1E-3	

Failure to tighten nut and bolt	4.8E-3	
Failure to install nut and bolt	6E-4	
Improper adjustment of mechanical linkage	1.7E-2	
Procedural error in reading instructions	6.5E-2	
Connecting hose improperly	4.7E-3	
Failure to pursue proper procedure by an operator		0.040
Installation error		0.013
Misinterpretation or misunderstanding of requirements by the operator		0.0076
Inadvertent or improper equipment manipulation by the operator		0.071
Improper servicing or re-assembly by the maintenance personnel		0.015

Table 1.5 Example of Level Two Matrix

Level Two	**Element 1**	**Element 2**	**Element 3**
Element 1	EL_{11}	EL_{12}	EL_{13}
Element 2	EL_{21}	EL_{22}	EL_{23}
Element 3	EL_{31}	EL_{32}	EL_{33}

Table 1.6 Example of Level Three Matrix

Element 1	A_1	A_2	A_3
A_1	A_{11}	A_{12}	A_{13}
A_2	A_{21}	A_{22}	A_{23}
A_3	A_{31}	A_{32}	A_{33}

Table 1.7 Comparison Scale

1	Both elements of equal importance
3	Left weakly more important than top
5	Left moderately more important than top
7	Left strongly more important than top
9	Left absolutely more important than top

1/3	Top weakly more important than left
1/5	Top moderately more important than left
1/7	Top strongly more important than left
1/9	Top absolutely more important than left

Table 1.8 Identified Task and Generic Human Error Data

Task	**Operator behaviour**	**Error Probability**
Derrick 1	Skill base	5.00E-03
Derrick 2	Skill base	5.00E-03
Derrick 3	Skill base	5.00E-03
Derrick 4	Knowledge base	5.00E-01
Vessel 1	Knowledge base	5.00E-01
Vessel 2	Rule base	5.00E-02
Vessel 3	Knowledge base	5.00E-01
Vessel 4	Skill base	5.00E-03
L.D 1	Skill base	5.00E-03
L.D 2	Skill base	5.00E-03
L.D 3	Skill base	5.00E-03
Net 1	Skill base	5.00E-03
Net 2	Skill base	5.00E-03
Gilson 1	Rule base	5.00E-02
Gilson 2	Knowledge base	5.00E-01

Table 1.9 RCO Matrix

Derrick	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5	RCO 6
Derrick 1						
Derrick 2						
Derrick 3						
Derrick 4						

Table 1.10 Summary of Results for Probability Element

	Derrick	Vessel	Lazy Decky	Net	Gilson	Total rating
RCO 1	4.73%	1.22%	1.40%	0.26%	0.92%	***8.53%***
RCO 2	3.63%	0.19%	0.84%	0.26%	0.42%	***5.34%***
RCO 3	6.70%	0.47%	2.17%	0.79%	1.28%	***11.42%***
RCO 4	4.73%	0.32%	0.75%	0.32%	0.81%	***6.94%***
RCO 5	1.25%	0.66%	1.79%	0.42%	0.84%	***4.97%***
RCO 6	6.93%	1.14%	2.37%	1.05%	1.31%	***12.81%***

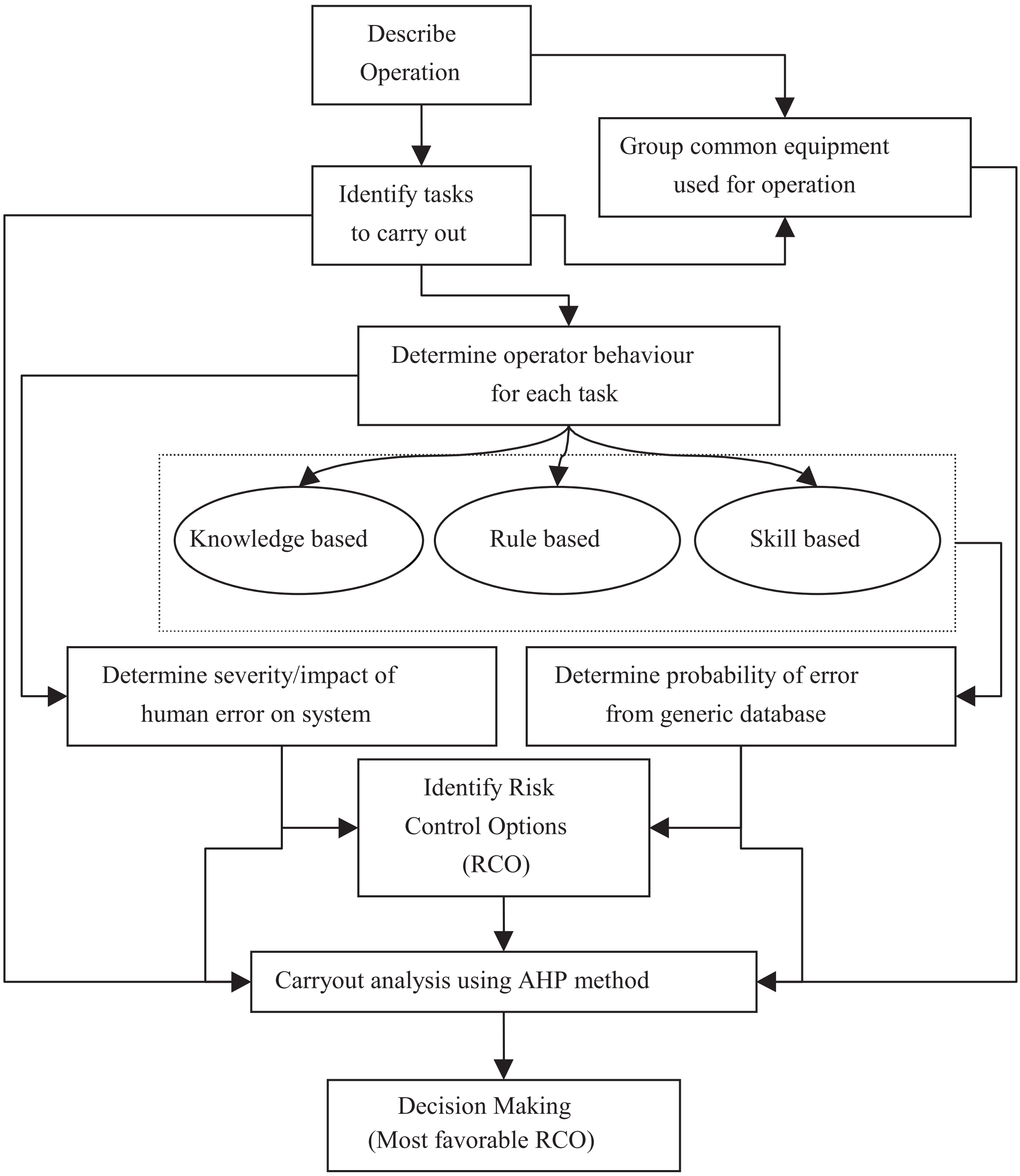
Table 1.11 Summary of Results for Severity Element

	Derrick	Vessel	Lazy Decky	Net	Gilson	Total rating
RCO 1	5.73%	0.76%	1.33%	0.22%	1.04%	***9.08%***
RCO 2	1.30%	0.30%	0.65%	0.22%	0.46%	***2.93%***
RCO 3	5.02%	0.85%	2.06%	0.78%	1.06%	***9.77%***
RCO 4	5.15%	0.67%	1.61%	0.60%	0.90%	***8.93%***
RCO 5	3.91%	0.55%	1.61%	0.50%	0.92%	***7.50%***
RCO 6	6.87%	0.85%	2.06%	0.80%	1.21%	***11.79%***

Table 1.12 Final Ranking of RCO

	Derrick	Vessel	Lazy Decky	Net	Gilson	Total rating
RCO 1	10.46%	1.98%	2.74%	0.48%	1.96%	***17.61%***
RCO 2	4.93%	0.49%	1.49%	0.48%	0.88%	***8.27%***
RCO 3	11.72%	1.33%	4.23%	1.57%	2.34%	***21.19%***
RCO 4	9.88%	0.99%	2.36%	0.91%	1.72%	***15.87%***
RCO 5	5.16%	1.21%	3.40%	0.92%	1.76%	***12.46%***
RCO 6	13.80%	1.99%	4.43%	1.85%	2.53%	***24.60%***

Figure 1.1 Flowchart of the approach



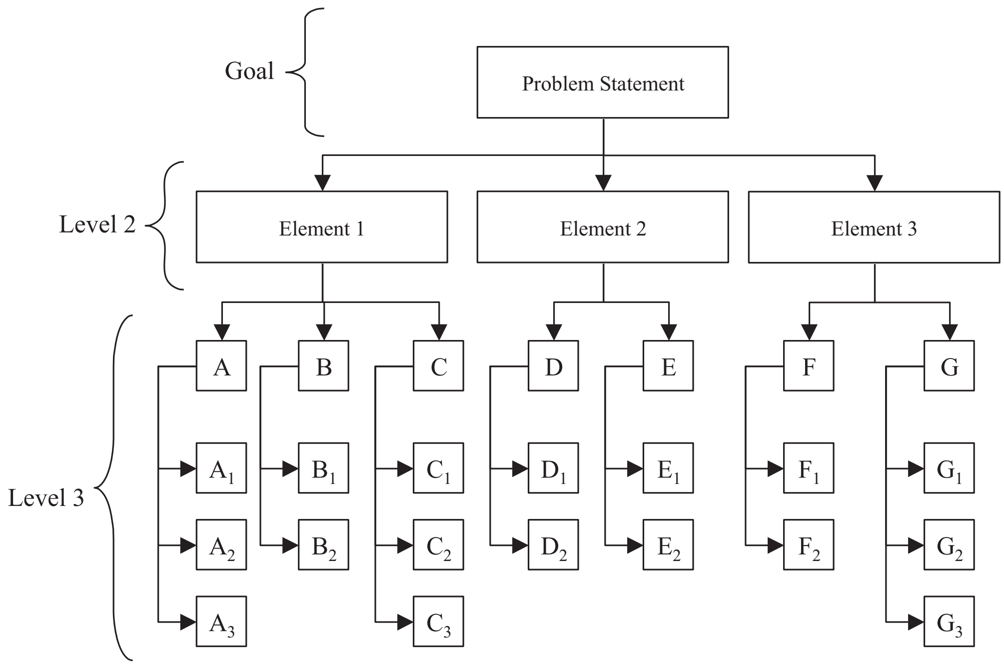


Figure 1.2 Example of hierarchy levels

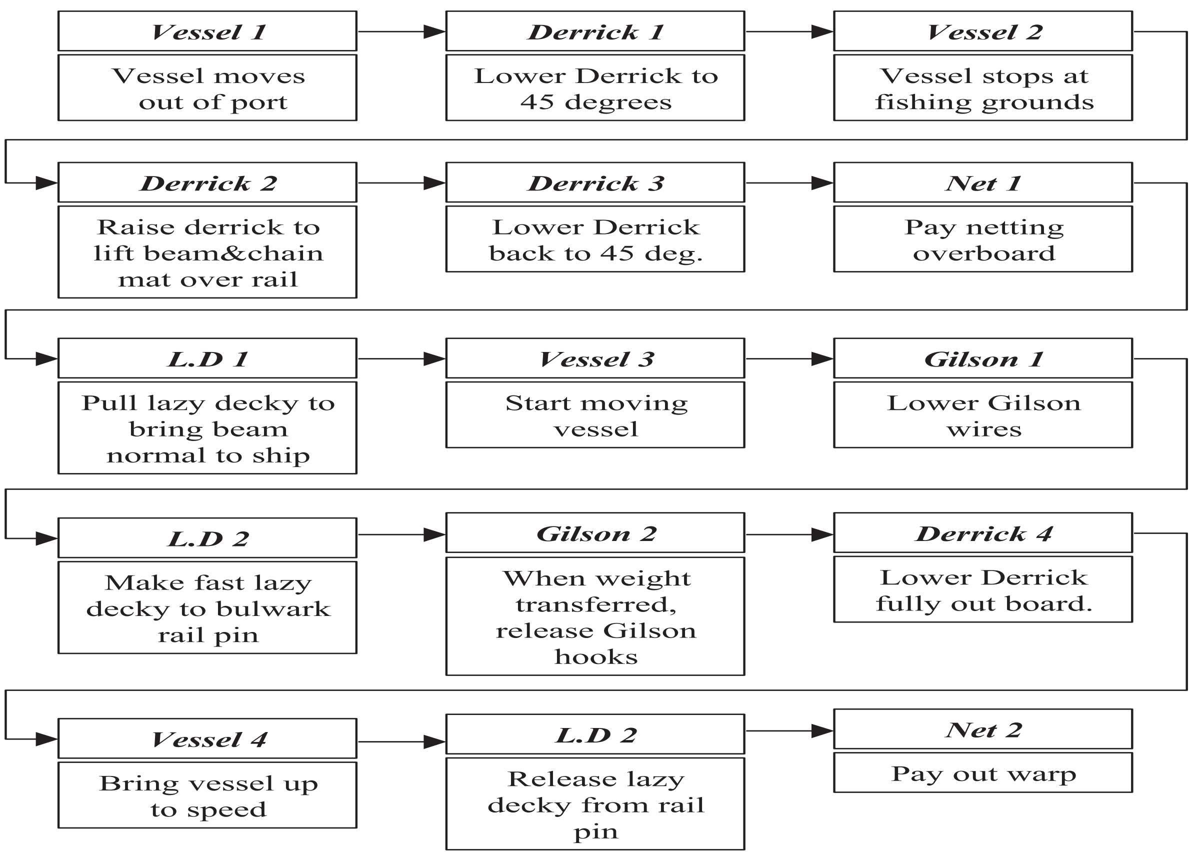


Figure 1.3 Diagrammatic representation of initial shooting operation

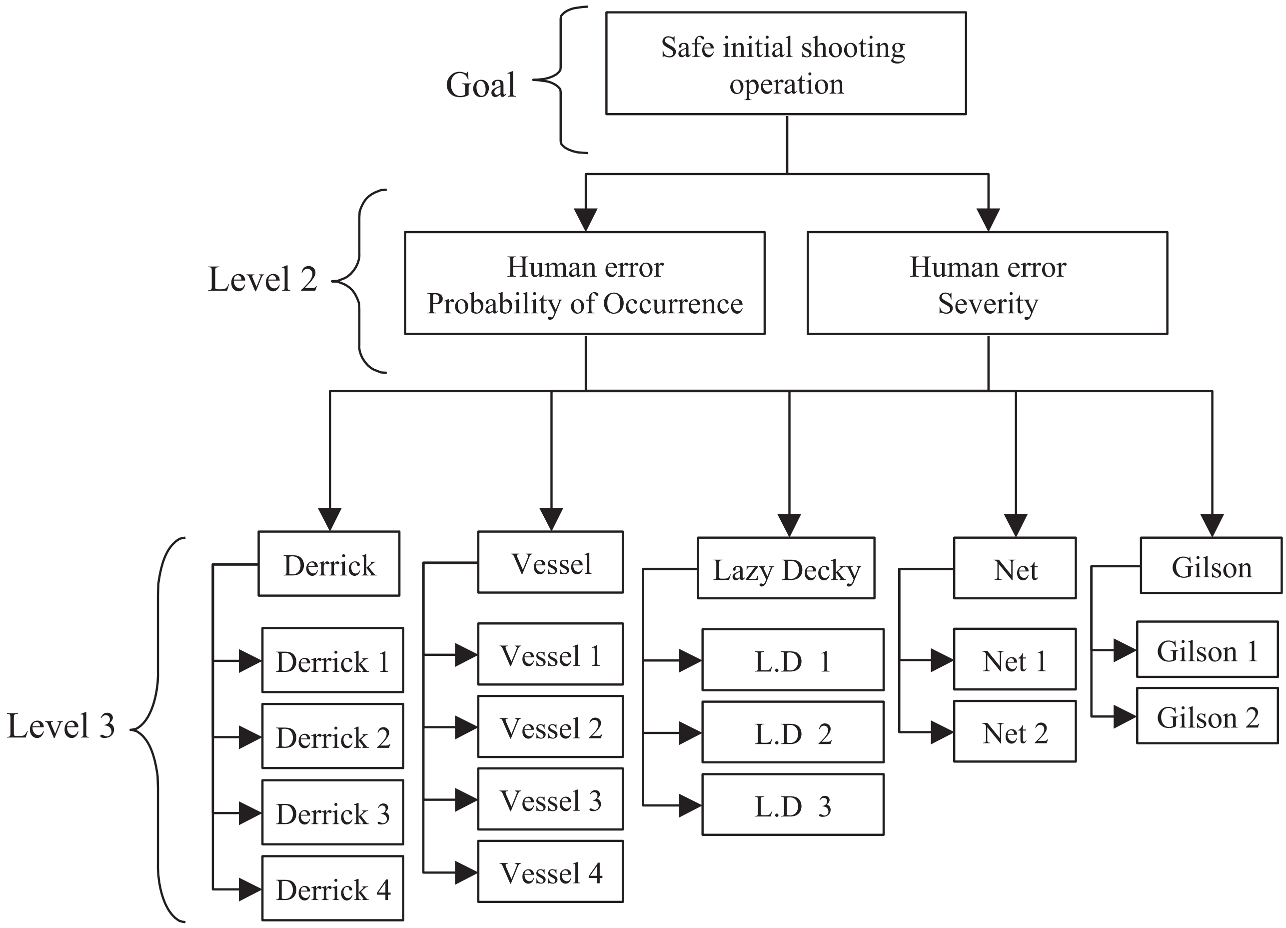


Figure 1.4 Initial shooting operation hierarchy levels