Fuzzy Inference As An Approach To Safety Management System (SMS) Analysis

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ABSTRACT

Safety analysis is one of the major areas of Ship Management company activity that frequently comes face to face with a nontraditional problem of "measurements of safety". The question arises of how to estimate or measure the safety level? There is no doubt that, post-accident, *a priori* statistical analyses or Formal Safety Assessment are not effective instruments to apply in a real-time interval, especially in emergencies. The majority of problems are directly linked with the human factor, which is very difficult to formalize.

The safety analyses generally serve as decision aids. Wise decisions are essential in any safety program. Human decisions depend on numerous factors that transcend requirements and physical response, and many of these can be captured mathematically using fuzzy logic. Fuzzy logic is conceptually easy to understand in SMS applications. It is flexible. With any given SMS it's easy to massage or layer more functionality on top of it without starting again from scratch, for example: to incorporate ISPS Code procedures into the already working SMS. Fuzzy logic is tolerant of imprecise data and there is a lot of such data in shipping. Fuzzy logic can model nonlinear functions of arbitrary complexity. Fuzzy logic can be built on top of the experience of maritime safety experts and it can be blended with conventional control techniques. The most impressive feature is that fuzzy logic is based on natural language.

The paper highlights some problems mentioned above and contains the research findings on evaluation of technical and human factor impact on safety at sea using *fuzzy logic* approach and applying such factors (linguistic variables) as safety, fatigue, OOW distractions, deficiencies, near misses, skill, level of education and training, technical failures, company policy/culture, etc.

1. Introduction

Why Use Fuzzy Logic in SMS analysis?

a. Fuzzy logic is conceptually easy to understand. SMS must be understandable for all personnel and the mathematical concepts behind fuzzy reasoning in SMS are very simple. What makes fuzzy logic nice is the "naturalness" of its approach and not its far-reaching complexity.

b. Fuzzy logic is flexible. With any given SMS it's easy to massage it, or layer more functionality on top of it, without starting again from scratch, for instance to incorporate ISPS Code into SMS.

c. Fuzzy logic is tolerant of imprecise data. Everything is imprecise if you look closely enough, but more than that, most things are imprecise even on careful inspection. Fuzzy reasoning builds this understanding into the process rather than tacking it onto the end. So we can improve SMS and its analysis without any restrictions.

d. Fuzzy logic can model nonlinear functions of arbitrary complexity. You can create a fuzzy system to match any set of input-output data (Human/Technical - safety data). This process is made particularly easy by adaptive techniques like ANFIS (Adaptive Neuro-Fuzzy Inference Systems), which are available in the Fuzzy Logic Toolbox of MATLAB software.

e. Fuzzy logic can be built on top of the experience of maritime safety experts. In direct contrast to neural networks, which take training data and generate opaque, impenetrable models, fuzzy logic lets you rely on the experience of people who already understand your SMS.

f. Fuzzy logic can be blended with conventional control techniques. Fuzzy systems don't necessarily replace conventional control methods. In many cases fuzzy systems augment them and simplify their implementation.

g. Fuzzy logic is based on natural language. The basis for fuzzy logic is the basis for human communication. This observation underpins many of the other statements about fuzzy logic.

Shipping is perhaps one of the most ancient industries in the World. The statement (*g)* is perhaps the most important one and deserves more discussion. Natural language, that which is used by seafarers and other people on a daily basis, has been shaped by thousands of years of human history to be convenient and efficient. Sentences written in ordinary language represent a triumph of efficient communication. We are generally unaware of this because ordinary language is, of course, something we use every day. Since fuzzy logic is built atop the structures of qualitative description used in everyday language, fuzzy logic is easy to use.

2. Foundations of Fuzzy Logic

Is there any relation between number of near misses ***N*** on board ship and probability of an accident? The answer is affirmative. Yes, there is such a relation and we can say that if a lot of *near misses* have occurred then the level of accident probability is high.

So, let us compose a rule of the following type:

N near misses are (always … never) followed by a serious accident

Try to identify ***N*** and fill up the space between "*always*" and "*never*" by the most detailed mode. Let us link in Table 1 the findings from Mcnail & Freiberger (1993) and statistical information about *near misses* from Hojnacki (2003). In general the sentence may be formed as follows:

(N) near misses are (ADVERB) followed by a serious accident

Here is the *linguistic variable* "*near miss*" which may have 20 *values* from *always* -to- *never* interval and may be described by ***N***. The main idea is that these adverbs have no crisp borders with respect to ***N***.

Table 1. The *values* (adverbs) of *linguistic variable* "*near miss*"

N	ADVERBS
1	3
300	always
261	very often
237	usually
222	often
222	rather often
216	frequently
216	generally
150	about as often as not
102	now and then
87	sometimes
84	occasionally
66	once in a while
48	not often
48	usually not
27	seldom
24	hardly ever
21	very seldom
15	Rarely
6	almost never
0	never

The theory of Fuzzy sets, on which basic ideas have been offered by American mathematician Lotfi Zadeh, allows us to describe qualitative, fuzzy concepts and knowledge of world around and to operate with this knowledge, with the purpose of reception of the new information. The methods of construction of information models based on this theory essentially expand traditional areas of computer applications and form an independent direction for scientifically applied researches which has received the special name - Fuzzy modeling.

Modeling of SMS is a system modeling, and SMS itself is a complex system consisting of a set of components connected among themselves. In this paper we do not put forth a problem of detailed SMS analysis. We want to show only opportunities of *Fuzzy Inference System* (FIS) for solving of such tasks with respect to some aspects connected to the human factor.

Fuzzy logic starts with the concept of a fuzzy set. A fuzzy set is a set without a crisp, clearly defined boundary. It can contain elements with only a partial degree of membership.

Now consider the set of safe depths for an oil tanker with a maximum draught of 10 meters. For instance, we are considering the risk of grounding of a vessel:

Q: Is the depth 10 meters safe for navigation?
A: 0 (no, or false)
Q: Is the depth 30 meters safe for navigation?
A: 1 (yes, or true)
Q: Is depth 11 meters safe for navigation?
A: 0.5 (may be yes, but not quite as much as a depth 12 meters).
Q: Is the depth 12 meters safe for navigation?
A: 0.8 (for the most part yes, but not completely, it depends on the vessel's speed, weather conditions, and so on).

What about the depth 11 meters? It "feels" like a part of the set of safe depths, but somehow it seems as though it should be technically excluded if the keel clearance is not enough for safety. So, the above *safe depth* tries its best "to sit on the fence". Classical or "normal" sets would not tolerate this kind of thing. Either you're in or you're out. Human experience suggests something different though: "fence sitting" is a part of life, and so it is a part of safety systems.

Of course we're on tricky ground here, because we're starting to take individual perceptions and safety culture background into account when we define what constitutes the safe depth.

But this is exactly the point. We're entering the realm where sharp-edged *yes-no* logic stops being helpful. Fuzzy reasoning becomes valuable exactly when we're talking about how people really perceive the concept "safe depth, safety" as opposed to a simple-minded classification useful for accounting purposes only. More than anything else, the following statement lays the foundations for fuzzy logic. In fuzzy logic the truth of any statement becomes a matter of degree.

Any statement can be fuzzy. The tool that fuzzy reasoning gives is the ability to reply to a *yes-no* question with a *not-quite-yes-or-no* answer. This is the kind of thing that humans do all the time (think how rarely you get a straight answer to a seemingly simple question) but it's a rather new trick for computers. How does it work? Reasoning in fuzzy logic is just a matter of generalizing the familiar *yes-no* (Boolean) logic. If we give "true" the numerical value of 1 and "false" the numerical value of 0, we're saying that fuzzy logic also permits in-between values like 0.2 and 0.7.

A Membership Function is presented by a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1.

The point of Fuzzy Inference System (FIS) is to map an input space (say, routine activities of crew members and shore staff) to an output space (say, safety) and the primary mechanism for doing this is a list of *if-then* statements called *rules*. All *rules* are evaluated in parallel and the order of the rules is unimportant. The rules themselves are useful because they refer to variables (linguistic variable) and the adjectives or adverbs (set of values) that describe those variables.

A single fuzzy *if-then rule* assumes the form:

if X is A then Y is B

where ***A*** and ***B*** are *linguistic values* defined by *fuzzy sets* on the ranges (*universes of discourse*) of ***X*** and ***Y*** respectively. The *if*-part of the rule "***X is A***" is called the *antecedent* or *premise*, while the *then*-part of the rule "***Y is B***" is called the *consequent* or *conclusion*, where ***X*** and ***Y*** are *linguistic variables*. An example of such a rule might be:

If there are a lot of near misses then the safety level is low

In general, the input to an *if-then rule* is the current value for the *input variable* (in this case, number of *near misses*) and the *output* is an entire *fuzzy set* (in this case a low level of safety). This set shall later be *defuzzified,* assigning one value to the output.

If we want to talk about the complexity of the area of navigation, we need to define the range by which the area's complicity can be expected to vary, as well as what we mean by the word *complex*. We may use a 3-point scale as is recommended in IMO Resolution A.953 (23) and use complexity levels as 1, 2 and 3.

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. There are two types of fuzzy inference systems that can be implemented in the Fuzzy Logic MATLAB Toolbox: *Mamdani-type* and *Sugeno-type*.
Mamdani's type was based on Lotfi Zadeh's 1973 paper on fuzzy algorithms for complex systems and decision processes.

3. Construction of FIS with respect to maritime safety (example)

Here we apply *input linguistic variables* ***X*** which it is possible to use to describe some hazards (NAV 49/INF.2, 2003) related to safety of navigation.

These hazards are divided into different classes: CULTURE, NAVIGATOR, PROCEDURES, TECHNICAL SYSTEMS, USER INTERFACE, OTHER. In Table 2, column 1 gives the name of a hazard and the name of a *linguistic variable* ***X***, column 2 indicates the set of values of ***X*** and column 3 proposes the Universum for ***X.***

Table 2. Fuzzy features of Hazards (**Culture**)

HAZARD/Linguistic variable X (*)	**T (set of values of X)**	**Universum of X**
1	**2**	**3**
1. OOW distractions (during the watch)/Distraction (1)	Small number Considerable number Dangerous number	[0,20]
2. Insufficient manning/Manning (2)	Sufficient Insufficient Dangerous	[0,10]
3. Cost cutting pressure/Investments into safety (2)	Insufficient Sufficient Super sufficient	[0,100]
4. Time pressure, keep schedule/Time (2)	To be late In time To arrive earlier	[-5,5] [hours]
5. Tired, pressure, not sufficient rest /Fatigue (1.7)	Insufficient Sufficient Super sufficient	[0,16] (hours)
6. Policy, responsibility of officers, etc./Responsibility (1)	Irresponsible About as often as not responsible	[0,100]
7. We have 1st priority. attitude /Safety culture (2.8)	Infringe always Infringe about as often as not Never	[0,100]
8. Insufficient simulator training/Training (1.8)	No training Poor Medium High	[0, 100]
9. High operational speed/Speed (2.2)	Full Half Slow	[2,18] knots
10. Company policy/culture /Company policy (2)	Poor High	[0,300] near misses
11. Not optimized training/Training programs (1.7)	Insufficient Sufficient Super sufficient	[0,100]

* Identified hazard's IMPORTANCE to the shipping industry: *1 = Is regarded as a large problem for the industry, 2 = Is regarded as a moderate problem for the industry, 3 = Is regarded as a minor problem for the industry,* (NAV 49/INF.2 ,2003).

The other classes of hazards can easily be presented also in Table 2 manner:

Table 3. Other hazards

Navigator: 12. Unfamiliar with vessel/bridge 13. Dependence on technology 14. Incapacitation 15. Incorrect use of equipment 16. Misjudgment when approaching quay, in narrow waters 17. Underestimate weather conditions (distance to hurricanes, poor training for these situations, etc.) 18. Misjudgment of traffic situations **Procedures:** 19. Communication between navigators, misunderstandings (may be measured in communication breakdowns) 20. Communication with pilot (linguistic problems, etc.) 21. Heavy traffic, many simultaneous situations (per watch) 22. Interaction, minor/leisure traffic 23. Navigational rules not known 24. GPS assisted /Radar assisted collision 25. Too many company procedures to follow/paperwork 26. Checklists are not used as a tool, but as a goal in itself 27. Insufficient/wrong procedures	**Technical systems:** 28. Insufficient radar functionality 29. Quality of equipment (ECDIS (update), etc.) 30. Technical failure (power supply) 31. Communication equipment failure 32. Large vessels, difficult to maneuver 33. (Integrated Nav. System/Integrated Bridge System) failure (incl. software) 34. GPS malfunction 35. GPS jumps 36. Gyro failure 37. Autopilot malfunction 38. Hard rudder as a result of loss of rudder feedback system **User interface:** 39. Poor bridge design, physical work conditions 40. Too much information (AIS, etc.) 41. Barriers regarding poor user interface 42. Alarm confusion 43. Local conditions (poor quay, marking, anchoring conditions) 44. Complex operating procedures compensating for poor technical systems **Other:** 45. Sabotage (spoofing of GPS signals, lead/force vessel on ground.) 46. Complexity of navigation area

The following human-related factors applied for accident investigation (BERTRANC, 2000), may be structured in the same way using appropriate *linguistic variables*.

Table 4 (a) Human-related factors applied in accident investigation

People factors: 47. Ability, skills, knowledge of the people involved 48. Personality (mental condition, emotional state) 49. Physical condition (medical fitness, fatigue, use of alcohol or drugs) 50. Activities prior to the accident/occurrence 51. Assigned duties at the time of accident/occurrence 52. Actual behavior at time of accident/occurrence 53. Attitude	**Working and living conditions:** 54. Level of automation 55. Ergonomics of equipment and the working environment 56. Adequacy of living conditions 57. Adequacy of food 58. Opportunities for recreations 59. Vibrations, heat, noise ship motion **Ship factors:** 60. Design 61. State of maintenance 62. Equipment (availability, reliability) 63. Cargo characteristics, including securing, handling and care 64. Certificates

Table 4 (b) Human-related factors applied in accident investigation

Organization on board:	Shore side management:
65. Division of tasks and responsibilities	75. Policy on recruitment
66. Composition of the crew (competence/nationality)	76. Safety policy and philosophy
67. Workload (both overload or underload)/complexity of tasks	77. Management commitment to safety
	78. Scheduling of leave periods
68. Work hours/rest hours	79. General management
69. Procedures and standing orders	80. Assignment of duties
70. Communication (internal and external)	81. Ship-shore communication
71. On board management and supervision	**External influences and environment (Navigation area):**
72. Organization of on board training and drills	
73. Teamwork	82. Weather and sea conditions
74. Planning of work	83. Port and transit conditions (VTS, pilots etc.)
	84. Traffic density
	85. Ice conditions
	86. Regulations, survey and inspections

So, how to evaluate the safety? There is no doubt that safety level is a function of all variables mentioned above and this set, frankly speaking, is not complete.

For example, we want to evaluate safety as a function of 3 *input linguistic variables* in some not extended time interval: *navigation area, number of OOW distractions and number of near misses.*
Let us suppose that their *Membership Functions* will be as follows in Fig.1:

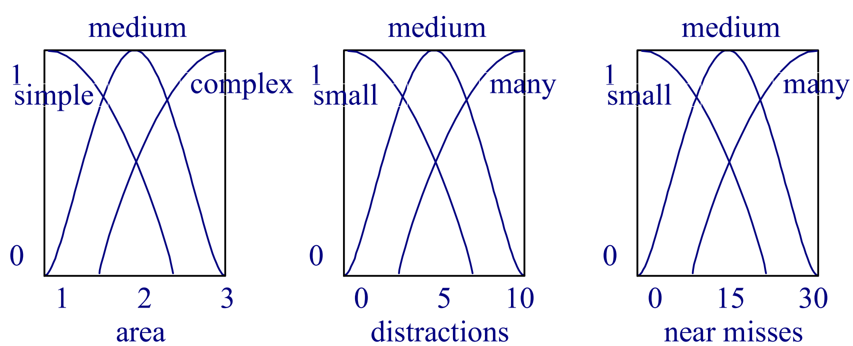

Fig.1 Membership Functions of input variables

Safety as a probability of accidents is designated to be *the output linguistic variable*.
Let us suppose that its Membership Functions will be as follows in Fig.2.

We selected the output *Membership Functions* in accordance with data from the frequency (Table 1). Number of near misses is reduced the ***N*** 10 times, guarding the appropriate proportions with linguistic values taken from the above said frequency table, supposing that time interval for evaluation is not very extended.

We composed the set of 27 fuzzy *if-then rule*s of the following type:
1. If (navigational area is simple) and (number of distractions is small) and (number of near-misses is small) then (safety has a high level) …
27. If (navigational area is complex) and (there are many distractions) and (there are many near-misses) then (safety has a low level).

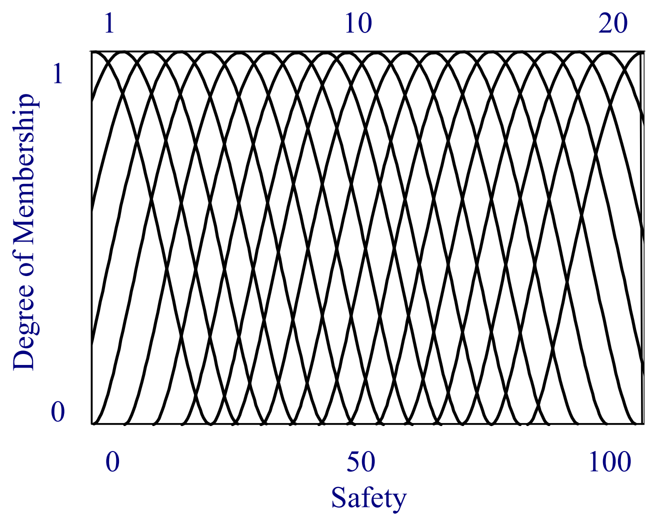

Fig. 2 Membership Functions of output variable *safety*

So, the FIS has of the following structure:

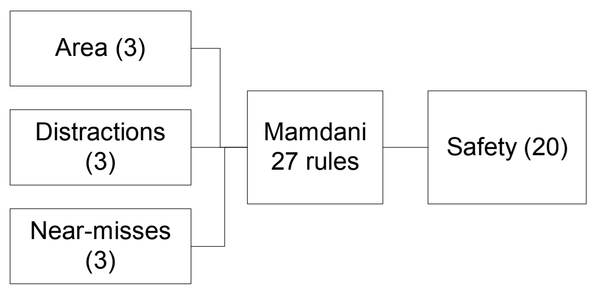

Fig. 3 FIS safety system analysis structure (3 inputs, 1 output, 27 rules)

The graphic results are presented on Fig. 4 and Fig. 5:

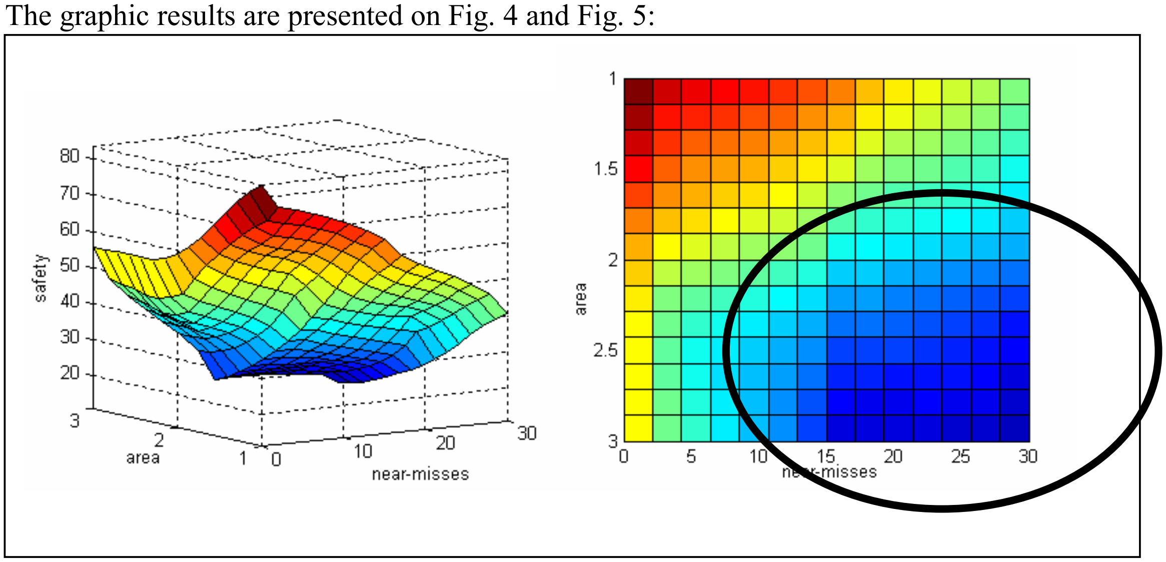

Fig. 4 Safety surface as a function of *area complexity* and number of *near misses*

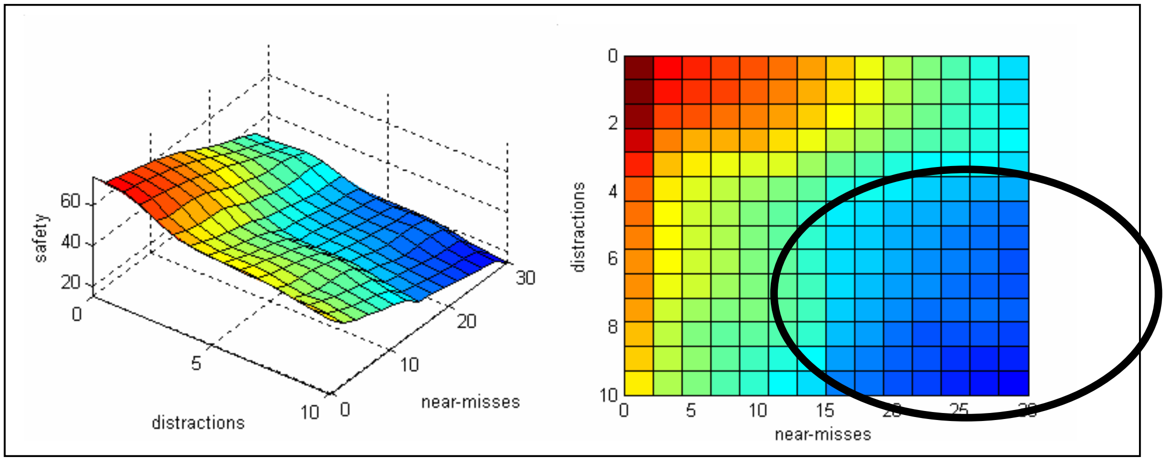

Fig. 5 Safety surface as a function of number of *OOW distractions* and number of *near misses*

4. Results and Discussion

Figures 4 and 5 show the safety level as a function of 3 components. Ellipses outline the most dangerous areas of 20% level of safety. In principle the foundings obtained from this analysis are trivial, but they encourage us to go ahead in more comprehensive application of Fuzzy Sets for SMS analyzing and it’s "tuning".

The safety analyses generally serve as decision aids. Wise decisions are essential in any safety program. Human decisions depend on numerous factors that transcend requirements and physical response, and many of these can be captured mathematically using fuzzy logic. Fuzzy logic is conceptually easy to understand in SMS applications. It is flexible. With any given SMS it's easy to massage or layer more functionality on top of it without starting again from scratch, for instance to incorporate ISPS Code procedures into the already working SMS. Fuzzy logic is tolerant of imprecise data and there is a lot of such data in shipping. Fuzzy logic can model nonlinear functions of arbitrary complexity. Fuzzy logic can be built on top of the experience of maritime safety experts and it can be blended with conventional control techniques. The most impressive feature is that fuzzy logic is based on natural language.

5. Conclusion

We have produced a little investigation of safety on the basis of FIS showing, by our opinion, all the positive features of fuzzy logic mentioned above. The Matlab Manual was used to prepare the paper and we are happy, that to have become acquainted with such an easy, understandable manual and software (MATLAB Software, 2002).

We hope this is only the beginning of Fuzzy Sets implementation in Safety Management Systems research that will provide the opportunity for their optimal and effective "tuning".

Intensive development of various types of very important and useful regulations and standards in the shipping industry over the last few years is, in a lot of cases, not well enough coordinated with the quantity and quality of resources required to meet these regulations and standards and ensure their proper implementation. These resources, for example, are as follows: intellectual, educational, skill resources, technical, technological, informational, financial, human and time resources, etc.

Application of such “catalysts of efficiency and safety” as ISO and ISM Code standards without granting the appropriate resources to meet their provisions has led to the emergence of some negative tendencies, in which new terms and concepts have been generated, such as “paper safety”, “paper audit”, “paper quality”, etc. But in carrying out many such bureaucratic “paper procedures” to keep the “paper image” of a MET institution, a shipping company or a vessel resources are wasted and, in many cases, the level of quality and safety is reduced.

Safety and Quality systems in shipping need some type of "tuning". Such systems may be managed with the help of information obtained from Fuzzy Inference.

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