Scientific Journals
Maritime University of Szczecin

Zeszyty Naukowe
Akademia Morska w Szczecinie

2012, 30(102) pp. 109–114 **2012, 30(102) s. 109–114**

Applicability of fuzzy logic to the COLREG rules interpretation

Wykorzystanie logiki rozmytej do interpretacji prawideł COLREG

Zbigniew Pietrzykowski[1], Rafał Malujda[2]

Maritime University of Szczecin, [1]Faculty of Navigation, [2]Centre of Marine Technologies Transfer
Akademia Morska w Szczecinie, [1]Wydział Nawigacyjny, [2]Centrum Transferu Technologii Morskich
70-500 Szczecin, ul. Wały Chrobrego 1–2, e-mail: z.pietrzykowski@am.szczecin.pl

Key words: COLREGs, rules interpretation, fuzzy logic, decision support, Marine Navigation, Anti-Collision

Abstract

The correct analysis and assessment of navigational situation, taking into account the existing Collision Regulations, provides a basis for making the right decisions on a seagoing vessel. Such basis is important for ensuring the safety of navigation in different, often complex, situations.

The interpretation of the relevant rules is therefore of key importance. They contain generalizations arising from a multitude of possible scenarios at sea. The consequence of this is imprecision hindering interpretation of the rules. This is of particular concern in the implementation of those rules in navigational information systems and decision support systems. This paper provides a preliminary analysis, based on practical examples, of the applicability of fuzzy logic as a tool for the algorithm-based interpretation of International Regulations for Prevention of Collisions at Sea (COLREGs).

The COLREGs general concept shall be presented with an indication of the imprecision of rules in selected areas. For this purpose, the current methods of legal interpretation shall be presented and applied. This will allow to classify the COLREGs into two groups: crisp and imprecise. The real collision case shall be presented and discussed. The conducted preliminary considerations will help determine initially whether the incorporation of the principles of fuzzy logic in the law may facilitate interpretation of legal provisions by setting acceptable boundaries of such interpretation, and thus also the implementation of provisions in the navigational decision support systems.

Słowa kluczowe: przepisy MPDM, interpretacja przepisów, logika rozmyta, wspomaganie decyzji, nawigacja morska, antykolizja

Abstrakt

Prawidłowa analiza i ocena sytuacji nawigacyjnej, uwzględniająca obowiązujące przepisy MPDM, stanowi podstawę dla podejmowania trafnych – właściwych – decyzji na statku morskim. Ma to istotne znaczenie dla zapewnienia bezpieczeństwa żeglugi w różnych, często złożonych, sytuacjach.

Kluczowa w wielu przypadkach jest interpretacja wymienionych przepisów. Zawierają one uogólnienia, wynikające z mnogości możliwych do wystąpienia sytuacji. Konsekwencją tego są nieprecyzyjności utrudniające interpretację przepisów. Dotyczy to w szczególności implementacji wymienionych przepisów w nawigacyjnych systemach informacyjnych i wspomagania decyzji. Przedmiotem artykułu jest wstępna analiza, na bazie przykładów praktycznych, możliwości zastosowania logiki rozmytej jako narzędzia do zalgorytmizowanej interpretacji prawideł „Międzynarodowego prawa drogi morskiej".

W artykule przedstawiona została istota COLREG's wraz ze wskazaniem obszarów nieprecyzyjności zapisów wybranych prawideł. W tym celu omówiono i wykorzystano aktualnie funkcjonujące sposoby wykładni (interpretacji) przepisów prawnych. Pozwoli to na próbę oceny, które z przepisów COLREG's można sklasyfikować jako ostre, a które jako nieprecyzyjne. Posłużył do tego wybrany przez Autorów stan faktyczny kolizji statków. Przeprowadzone rozważania pozwoliły wstępnie ocenić, czy naniesienie siatki zasad logiki rozmytej na przepisy prawne może ułatwić ich interpretację poprzez wytyczenie dopuszczalnych granic takiej interpretacji, a tym samym także implementację przepisów w nawigacyjnych systemach wspomagania decyzji.

Introduction

The growing amount and scope of navigational information available on ships board leads to a situation where making decisions in difficult and complex situations may go beyond the abilities of decision makers. One way to solve this problem is to build decision support systems. Their basic functions include automatic acquisition and distribution of navigational information, analysis and assessment of a navigational situation, solving collision situations and interaction with the navigator. The situation analysis, assessment and determination of solutions require interpretation of a navigational situation from the viewpoint of binding legal regulations known as the COLREGs, i.e. the Convention on International Regulations on Prevention of Collisions at Sea, done at London on 20 October 1972 under the auspices of the IMO [1]. It replaced similar previous regulations of 1960. Ratified by Poland on 6 May 1977, the Convention contains provisions for rules of the road for sea-going ships: definitions of ships, arrangement of lights and shapes, conduct of vessels in various visibility conditions. Basic difficulties in interpreting those rules are generalizations and associated imprecision. They result from restrictions and imperfection of navigational systems and equipment of the time the regulations were adopted, including the amount, scope and accuracy of obtained information. The specific character of these rules is additional difficulty – they were prepared to perform their ordering functions in a specific field of marine navigation, which requires that many circumstances and customs have to be taken into account. Although these are hard to be codified in specific texts of provisions, they have to be taken into account while analyzed, which makes it very difficult to read out these rules in terms of classical bivalent true / false logic.

A good example is provided by Rule 14, concerning two meeting vessels. According to Rule 14a, *When two power-driven vessels are meeting on* ***reciprocal or nearly reciprocal courses*** *so as to involve risk of collision each shall alter her course to starboard so as to each shall pass on the port side of the other*. Besides, *such a situation shall be deemed to exist when a vessel sees the other ahead or nearly ahead and by night she could see the masthead lights of the other in line or nearly in a line and/or both sidelights and by day she observes the corresponding aspect of the other vessel*.

Like in case of all legal regulations, there is a need for applying proper methods of interpretation of maritime regulations, where Collision Regulations are those of our concern. The standard approach is to "put them through" the filter of law interpretation methods. A non-standard approach would be "putting through" the filter of fuzzy logic methods allowing to write them down formally (mathematically), that may constitute an alternative interpretation of the law.

Interpretation of the law

Concept and types of the interpretation of the law

Interpretation of the law, in its broad meaning, is the decoding of legal rules from a valid legal text. In other words, it is a reconstruction of a legal rule from legal provisions and determination of its meaning [2].

Types of interpretation:

1) Linguistic interpretation – interpretation based on the exact wording of the language in which the text was formed.
2) Extra-linguistic interpretation – comprises three kinds: teleological or purposive interpretation (based on the purpose of the legal rule), systemic (based on the place of the rule in the legal system) and functional interpretation (based on the functionality of the rule in the legal system):
   a) teleological interpretation – a statute provision has to be interpreted, so that it becomes the most useful measure for achieving the statute intention;
   b) functional interpretation – interpreting a legal regulation its function should be taken into account;
   c) systemic interpretation – assumption that a rule in a given legal act is not placed accidentally, but it results from rational actions of the legislature. Such interpretation may imply that the rule may have less significance in relation to the text of a higher order regulation or rule;
   d) logical interpretation – uses logic methods:
      - *Argumentum a contrario* – there are some As, some Bs, some Cs (if we negate A, then there cannot be B, or C; if we negate B, then there can be A or C);
      - *Argumentum a fortiori*:
        - *argumentum a maiori ad minus* – if someone was obliged (or permitted) to do more, then he was obliged (or permitted) to do less as well);
        - *argumentum a minori ad maius* – if someone was prohibited to do less, then all the more he was prohibited to do more.

Otyher types of interpretation:

1) Literal interpretation (interpretatio declarativa) – takes place when among various meanings

obtained through different interpretation directives, the meaning established by linguistic directives is chosen.
2) Extensive interpretation (interpretatio extensiva) – takes place when comparing the scopes of a legal act, obtained by different interpretation directives, we choose the meaning resulting from extra-linguistic directives and it is wider than the linguistic meaning.
3) Restrictive interpretation (interpretatio restrictiva) – consists in choosing, out of different scopes of legal regulation obtained by extra-linguistic directives, the one that is narrower than the linguistic sense [2].

Rules of the interpretation of the law

Regardless of the adopted interpretation of the law, certain rules should be applied; the main ones are as follows:

1) all legal acts should be interpreted literally (for important reasons, however, they can be interpreted extensively or restrictively);
2) provisions of penal law must have literal interpretation;
3) provisions of tax law must have literal interpretation;
4) provisions of penal law must not have extensive interpretation;
5) provisions of tax law must not have extensive interpretation;
6) exceptions must not have extensive interpretation;
7) special regulations (*lex specialis*) must not have extensive interpretation;
8) authorizing regulations must not have extensive interpretation;
9) freedoms and powers may have extensive interpretation [3].

Interpretative directives

Interpretative directives indicate how to determine the exact meaning and scope of the legal language.

There are:

1) 1st degree directives – recommending how legal regulations should be interpreted;
2) 2nd degree directives – these indicate which 1st degree directives should be used for a given interpretation, and establish the sequence at which such directives should be used. They define the criteria for the choice of one of incongruent meanings obtained by 1st degree directives [3].

Legal loopholes

Legal loopholes are areas in the law that are insufficiently explicit, comprehensive or even not regulated at all and allow the law to be circumvented.

The following legal loopholes are distinguished:

1) axiological (or real) – when the law does not regulate a given case or event. Such situation is remedied by creating a specific legal norm;
2) thetic (or apparent) – when an act regulates an event imprecisely. Then to eliminate such loophole one should refer to an analogy from a statute: then we make use of a statute regulating a similar case, or to an analogy from the law, we make use of basic legal principles;
3) logical – when a given event is regulated by at least two norms or at least two legal acts. Then we use the acts: chronological (we consider the latest act put into force), hierarchical (we apply an act of higher order, if still the matter cannot be settled) or scope-related (those describing a given case in most detail) [3].

Restrictions of the legal logic and its rules in relation to the algorithmization of COLREGs interpretation

Legal logic, also known as practical logic, among others includes the use of logic rules, mainly rules of legal inference, for the interpretation of legal regulations.

Undoubtedly, a restriction of legal logic rules is that they are based on the so called bivalent logic, where no intermediate values are accepted between true (1) and false (0). In this context the algorithmization of COLREGs would have a restricted (i.e. wrong) character because actual states between these values (also subject to assessment) would have to be excluded from an analysis.

Fuzzy logic

Representation of imprecise and ambiguous terms

Legal terms, like in other areas of human activity, are often ambiguous and imprecise. One way to describe such terms and use them in inference processes is the theory of fuzzy sets. This theory enables a formal description of imprecise and ambiguous terms.

According to one definition a fuzzy set is a set of pairs [4]:

$$A = \{x, \mu_A(x)\}, \forall x \in X \tag{1}$$

where

$$\mu_A(x): X \to [0,1] \tag{2}$$

is a fuzzy set A membership function, that to each element $x \in X$ assigns its degree of membership to a set A, $\mu_A(x) \in [0, 1]$. If X is a space with a finite number of elements, $X = \{x_1, x_2, ..., x_n\}$, then fuzzy set $A \subseteq X$ is written in this form:

$$A = \{x_1, \mu_A(x_1)\}, \{x_2, \mu_A(x_2)\} \dots \{x_n, \mu_A(x_n)\} \quad (3)$$

or

$$A = \mu_A(x_1)/x_1 + \mu_A(x_2)/x_2 + \dots + \mu_A(x_n)/x_n \quad (4)$$

The term "particular caution" is an example of ambiguity and imprecision. Used in the law on road traffic [5], an area of law related to COLREGs, it is defined as caution requiring increased attention and proper adjustment of the traffic participant's behaviour. In parallel, the terms "caution" and "no caution" are in use. By using the tools of the fuzzy sets theory we can present them as fuzzy sets A_1, A_2 and A_3, defined on a universe of vehicle speeds [km/h]:

$$A_1 = 0/40 + 1/45 + 0/65$$

$$A_2 = 0/40 + 0.5/45 + 1/60 + 0.5/65 + 0/75$$

$$A_3 = 0/70 + 0.5/75 + 1/90$$

For our considerations two concepts are essential: linguistic variable and linguistic value. The linguistic variable is understood as a certain quantity (input, output, state variable) that is evaluated in linguistic terms, and the linguistic value is verbal evaluation of a linguistic quantity [6]. Linguistic values occur together with linguistic variables they refer to. These statements can be formalized by assigning some fuzzy sets to them. This also refers to the example presented earlier. We can assume that "caution" is a linguistic variable, while "particular caution" and "no caution" are its linguistic values.

Fuzzy relations

Similarly to a fuzzy set, a fuzzy relation is a generalization of a crisp relation. It allows to describe imprecise interrelations. In place of a discrete two-element set {0, 1} we introduce a continuous interval [0, 1] for a membership function.

We define a fuzzy two-argument relation R between two crisp sets X and Y as a fuzzy set defined on Cartesian product $X \times Y$ as a set of pairs:

$$R = \{(\mu_R(x,y),(x,y))\}, \forall x \in X, \forall x \in X \quad (5)$$

where:

$$\mu_R(x,y): X \times Y \to [0,1] \quad (6)$$

is a membership function of fuzzy relation R, assigning to each pair (x, y), $x \in X$, $y \in Y$ its degree of membership $\mu_R(x, y) \in [0, 1]$, an intensity measure of fuzzy relation R between x and y.

As a fuzzy relation is a fuzzy set, all definitions and properties of fuzzy sets are conveyed onto fuzzy relations.

If we assume that three crisp sets are given $X = \{x\}$, $Y = \{y\}$, $Z = \{z\}$ with certain fuzzy relations R defined on $X \times Y$ and G on $Y \times Z$, with membership functions $\mu_R(x, y)$ and $\mu_G(y, z)$, the superposition of fuzzy relations of the max-min type is defined [4, 7] as a fuzzy relation $R \circ G$ with the membership function:

$$[\mu_R(x,z) \wedge \mu_G(y,z)], \forall x \in X, \forall z \in Z \quad (7)$$

Basic fuzzy relations are similarity and ordering fuzzy relations. Fuzzy relation S on $X \times X$ is called a similarity relation if it is reflexive (6), symmetrical (7) and transitive in the max-min sense (8):

$$\mu_S(x,x) \geq 1 \forall x \in X \quad (8)$$

$$\mu_S(x,y) = \mu_S(y,x) \forall x, y \in X \quad (9)$$

$$[\mu_S(x,z) \wedge \mu_S(y,z)], \forall x \in X, \forall z \in X \quad (10)$$

Like for crisp relations, fuzzy ordering relations, or fuzzy orders, are defined. The fuzzy order is a fuzzy relation R on $X \times X$ that is transitive in the max-min sense (10).

Fuzzy conditional statement. Superposition inference rule

Fuzzy conditional statements are used for representing relations between linguistic variables. These statements allow to describe cause-and-effect relations between the adopted linguistic variables. For linguistic variables L and K such that linguistic variable L is a fuzzy set A on X and a linguistic value of linguistic variable K is fuzzy set B on Y, then the fuzzy statement has this form:

$$\text{IF } L = A \text{ THEN } K = B \quad (11)$$

or simply

$$\text{IF } A \text{ THEN } B \quad (12)$$

It is further assumed that the above fuzzy conditional statement

$$\text{IF } A \text{ THEN } B = A \times B \quad (13)$$

is equivalent to the Cartesian product of two fuzzy sets A and B. The product is, in turn, a fuzzy relation on $X \times Y$.

Basic rules of the classical logic are *modus ponens* and *modus tollens* that have the following methods of inference [8]:

– *modus ponens*:
  premise: M
  implication: $M \to N$ (14)
  conclusion: N
– *modus tollens*:
  premise: $\overline{M}$
  implication: $M \to N$ (15)
  conclusion: $\overline{N}$

where generalized fuzzy inference rules are equivalent to rules (12) and (13). The fuzzy *modus ponens* has this form:

premise: L is A'
implication: IF L is A THEN K is B (16)
conclusion: K is B'

where L and K are linguistic variables, A' and A are linguistic values of linguistic variable L, fuzzy sets on X, while B' and B are, respectively, linguistic values of linguistic variable K, and are fuzzy sets on Y.

According to the definition of superposition inference rule [4], if R on $X \times Y$ is a fuzzy relation representing the relation between two linguistic variables, expressed as a fuzzy conditional statement, and one linguistic variable assumes a linguistic value A' on X, then the implied linguistic value of the other linguistic variable is defined by the superposition of A' and R

$$B' = A' \circ R \tag{17}$$

that for the max-min approach has this form:

$$[\mu_A(x) \wedge \mu_R(x,y)],\ \forall y \in Y \tag{18}$$

The fuzzy inference system

Sets of fuzzy rules in the form of rule bases gain increasingly wider applications for description and control of systems and processes. They are components of fuzzy inference systems (Fig. 1).

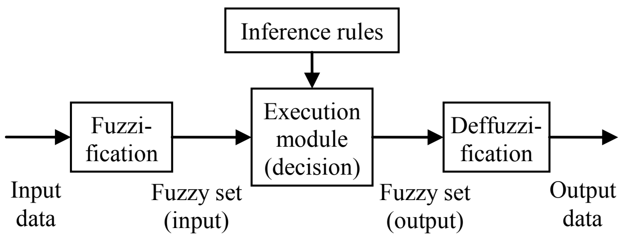

Fig. 1. Fuzzy inference system diagram
Rys. 1. Schemat systemu wnioskowania rozmytego

The fuzzificator transforms a set of input data into a fuzzy set (sets) described by membership functions. The executive module implements defined fuzzy inference rules. The output quantity of the inference block is one or more fuzzy sets. The defuzzificator function is to transform fuzzy sets of inference results into a determined crisp output value.

These systems find applications in, among others, problems of process or classification control. Bearing in mind the fact that problems of interpretation of regulations such as COLREGs can in most cases be brought down to the classification problem, it seems purposeful to consider a possible use of fuzzy inference systems in the interpretation of the mentioned regulations. The use of fuzzy rules will permit, in particular, to take into account imprecision and ambiguities of terms while interpreting those regulations.

An example of COLREGs imprecision

The collision between the "Gotland Carolina" and "Conti Harmony" is an example confirming the need and benefits of using methods of fuzzy logic as an auxiliary tool in legal analysis. The collision occurred at 09:26 local time on 19 April 2008, 22 Nm south of Ra's al Kuh Cape (Iran) during daylight in very good visibility conditions.

An analysis of collision causes

"Gotland Carolina"'s third officer made a mistake that navigators quite frequently make. According to the authors of the article [9] "… the navigator on board the "Gotland Carolina" had probably come to a conclusion that if a faster ship than his was located below his beam, then it was a case of overtaking (Rule 13). Consequently, he took no preventive action as prescribed by Rule 17 of COLREGs. The "Conti Harmony" was in fact faster and was approaching the "Gotland Carolina" from behind her beam (relative bearing 097º), but the regulations specify that the limit between overtaking and crossing courses is 112.5º, a fact navigators neglect only too often. The watch officer on the "Gotland Carolina" correctly qualified the situation and in the first stage of the encounter followed Rule 17. However, he did not take advantage of the possibility provided by paragraph a) ii), and the most importantly, he did not take action as prescribed by paragraph b) of the mentioned rule. What is most shocking in the event: neither of the vessel took any preventive action till the very moment of collision!"

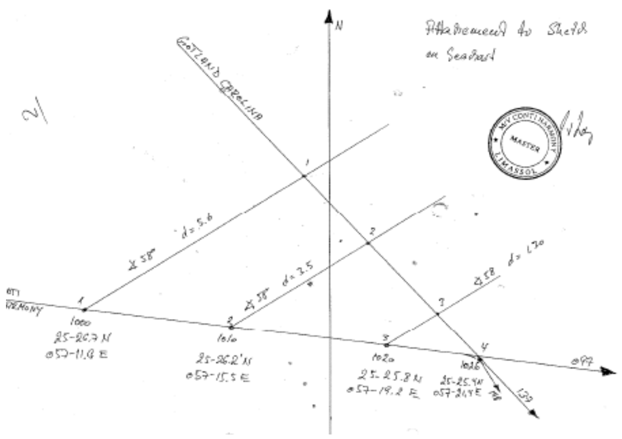

Fig. 2. Sketch drawn up on board the m/v "Conti Harmony" after the collision [10]
Rys. 2. Szkic sytuacji sporządzony na pokładzie „Conti Harmony" po kolizji [10]

Identification and classification of an encounter situation

Logic rules can be used for assessment of navigational situations from two perspectives, i.e. from the perspective of each meeting ship. The assessment would take into account inaccuracies and imprecision concerning the moment of qualifying an event as an encounter and the identification of encounter parameters. One advantage of such approach would be the identification of discrepancies in navigators' classification from own ship perspective (relative bearing) and both ships' view and indication that the actual situation has to be mutually recognized and manoeuvres agreed on. One may also consider making a decision that might be called a meta-decision, one that will be suited to the realities of a given encounter and take account of individual perspectives of each ship.

A close-quarters situation

Another area where fuzzy logic rules can support the interpretation of legal regulations is situational changeability in time, a typical feature of each vessel encounter. In this respect, the navigational decision support system could supply decisions modified in time, i.e. taking into account the fact the vessels keep getting closer to each other. This may apply to the identification of various phases of vessel encounter and obligations resting on both navigators in each encounter phase:

1) for the stand-on vessel: 1. observation, 2. keeping course and speed, 3. taking action if the give-way vessel does not act; 4. taking immediate action in a close-quarters situation;
2) for the give-way vessel: 1. observation, 2. making a decision, 3. taking action, 4. taking immediate action in a close-quarters situation.

In the "Gotland Carolina–Conti Harmony" accident the collision happened because no proper actions were taken by either vessel in certain encounter phases:

– give-way vessel: phases 2, 3 and 4;
– stand-on vessel: phases 3 and 4.

An analysis of the suitability of fuzzy logic

In the collision described herein from at least one perspective, i.e. one navigator of a colliding vessel, the actual situation was wrongly assessed. In other words, the situation preceding the accident was mistakenly qualified as subject to another rule of the COLREGS and consequently no actions were taken. In that case the choice of the proper rule was between Rules 13 and 15, as their provisions partly overlap, and then Rule 17, point a) ii) and clause b) of that rule were not respected.

One solution may be a description of COLREGs rules by the tools of fuzzy set theory. The linguistic variables and their linguistic values will have to be identified, additionally the values will have to be defined. On this basis fuzzy conditional statements and superposition inference rules can be formulated for use in the fuzzy inference system.

It appears that the submission of COLREGs rules to fuzzy modeling, based on navigators' experience and maritime court decisions to date will result in their formalized mathematical description and implementation for automatic interpretation in navigational decision support systems.

Conclusions

This article analyzes possible applications of fuzzy logic rules for the interpretation of Collision Regulations (COLREGs). Basic principles of the interpretation of the law are briefly presented. Principal terms, methods and tools of fuzzy logic are characterized in reference to their use in regulation interpretation. After presenting an actual case of a marine accident the authors indicate potential areas of fuzzy logic use in COLREGs interpretation.

The analysis confirms that it is possible and purposeful to use fuzzy logic in COLREGs interpretation. The next step will be the implementation of formalized records of selected COLREGs rules, so that they will be incorporated in a computer-aided navigational decision support system.

References

1. COLREGs 1972, Convention on the International Regulations for Preventing Collisions at Sea, International Maritime Organization.
2. ZIELIŃSKI M.: Legal interpretation. Principles, rules, directives. Warszawa 2008 (in Polish).
3. MORAWSKI L.: Rules of legal interpretaion. Toruń 2010 (in Polish).
4. KACPRZYK J.: Multi-stage fuzzy control. WNT, Warszawa 2001 (in Polish).
5. Traffic Law Act of 20.06.1997 (in Polish).
6. PIEGAT A.: Fuzzy modeling and control. EXIT, Warszawa 1999 (in Polish).
7. KACPRZYK J.: Fuzzy sets in system analysis. PWN, Warszawa 1966 (in Polish).
8. RUTKOWSKI L.: Methods and techniques of artificial intelligence. PWN, Warszawa 2009 (in Polish).
9. WOŁEJSZA P., MAGAJ J.: Analysis of possible avoidance of the collision between m/v "Gotland Carolina" and m/v "Conti Harmony". Annual of Navigation, 16, Gdynia 2010, 165–172.
10. Danish Maritime Administration, Casualty investigation reports, www.dma.dk.