Logic Programming for Developing an Interactive Explainable Naval Decision Support System

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Abstract. The increasing complexity of naval traffic necessitates robust decision support systems that enhance safety through compliance with the International Regulations for Preventing Collisions at Sea (COLREGs). This paper proposes using logic programming to develop explainable decision support systems tailored for encounter situations in maritime navigation. Logic programming is utilized to provide recommendations with clear, human-understandable explanations. The framework addresses various encounter scenarios by encoding the COLREGs rules into logical constructs to conclude appropriate actions and facilitates automated reasoning, ensuring rapid and accurate response. Our system is designed to collect sensor data, assess risk levels, and recommend optimal actions that comply with maritime regulations. The inherent explainability of logic programming allows generating traceable and transparent decision paths. Mariners can comprehend the underlying rationale that supports trusted decision-making onboard. The paper explores the implementation of this system, detailing its architecture, inference mechanisms, and integration with Automatic Identification System (AIS) messages. An Interactive eXplainable Decision Support System (IXDSS) was developed to demonstrate its effectiveness in diverse traffic scenarios while providing logical and visual explanations, including interactive 'what-if' analyses. IXDSS was evaluated using a standardized set of encounter scenarios, showing accurate scenario prediction, and its explainability was assessed qualitatively.

Keywords. XAI, Explainable decision support system, AIS, COLREGs, Prolog

1. Introduction

The rapid advancement of Artificial Intelligence (AI) has led to a growing integration of decision support systems (DSS) across domains such as healthcare [1], financial services [2], and autonomous systems [3]. However, the complexity and opacity of AI algorithms challenge trust and usability in high-stakes environments [4]. EXplainable Artificial Intelligence (XAI) has therefore motivated the development of eXplainable Decision

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Support Systems (XDSS) [5]. Through XDSS, AI predictions can be communicated through interpretable mechanisms that clarify decision formulation [6].

In autonomous vehicles and robotic platforms such as Autonomous Surface Vehicles (ASVs), XDSS helps operators understand and justify AI-augmented decisions [7]. Studies show that logic- and rule-based approaches can enhance situational awareness and operational decision-making by providing structured explanations [5].

A user-centric design perspective remains central, emphasizing interfaces that intuitively convey AI reasoning [8]. Incorporating "What-if" analysis allows users to explore alternative scenarios and assess the reliability and robustness of AI recommendations [9].

This paper extends prior work on trust and explainability for ASV developers to include end users. To support real-time interactions, an Interactive eXplainable Decision Support System (IXDSS) has been developed. IXDSS delivers context-aware recommendations with user-friendly explanations to assist decision-making in ship navigation at autonomy level 1 [10, 11]. IXDSS facilitates responsible actions through clear rationale.

Building upon the rule-based framework in [12], which interprets encounter situations under the International Regulations for Preventing Collisions at Sea (COLREGs) [13], IXDSS reformulates statements as predicates in Prolog. In IXDSS, facts define the true predicate instances of the current situation, and rules use these predicates to infer new truths and recognize situations when their conditions are met. Real-time AIS [14] messages supply situational data for IXDSS to infer appropriate actions at different explanation levels. Recommendations and explanations are presented visually and textually. Users can explore "what-if" scenarios and compare the current context with prototypical situations to understand and justify system outcomes.

This paper is organized as follows. Section 2 reviews COLREGs and related systems. Section 3 presents the IXDSS architecture. Section 4 discusses evaluation. Section 5 concludes and outlines future work.

2. COLREGs-based Systems

This section briefly reviews the International Regulations for Preventing Collisions at Sea (COLREGs). It situates the proposed approach among systems that integrate these regulations with AI models and highlights the contribution of user-centered, explainable navigational guidance.

2.1. Encounter Situations in COLREGs

The COLREGs [13] define responsibilities during encounter situations where vessels' paths intersect, potentially leading to collisions. For vessels within visual range, Section II of Part B provides guidance.

- Rule 13 (Overtaking): The overtaking vessel must keep clear until safely past (Figure 1a).
- Rule 14 (Head-on): Each vessel alters course to starboard for a port-to-port passage (Figure 1b).
- Rule 15 (Crossing): The vessel with the other on its starboard side must give way (Figure 1c).

- Rule 16 (Give-way): The give-way vessel takes early, substantial, and apparent action.
- Rule 17 (Stand-on): The stand-on vessel maintains course and speed but may maneuver if the give-way vessel fails to act or collision becomes likely.
- Rule 18 (Hierarchy): Responsibilities vary by vessel type and maneuverability.

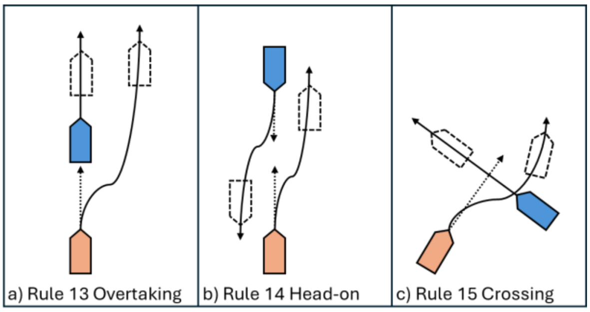

Figure 1. Actions need to be taken in different encounter situations.

Directional terms 'ahead,' 'astern,' 'port,' and 'starboard' are used as in Rule 21 (light arcs). Following [12], this paper refers to these regions as ship sectors (Figure 2a).

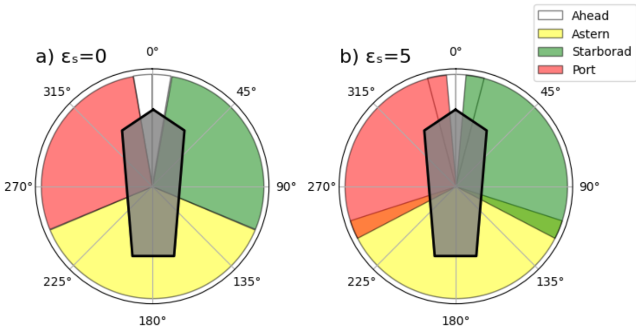

Figure 2. Ship sectors a) without overlapping $\varepsilon_s = 0$. b) with overlapping areas between sectors with $\varepsilon_s = 5$, a ship positioned in one of these overlapping areas can be perceived as being in two sectors simultaneously.

2.2. Encounter Situation Systems

Approaches for COLREGs compliance include rule-based systems [12], fuzzy logic [15], and deep reinforcement learning (DRL) [16]. DRL can adapt to complex scenarios and reduce human error [18], but experienced mariners and AI systems may respond differently to the same situations [18], underscoring the need for transparency, interpretability, and accountability [19]. DRL's "black-box" nature and computational demands complicate verification and deployment [17].

Rule-based systems offer transparent, interpretable processes grounded in domain knowledge, enabling assessment of compliance, rationale, and traceability. Although less adaptable than some learning-based models, they are well-suited for explainability.

Large Language Models (LLMs) have recently been explored for COLREGs-compliant decision-making. Their capacity to process natural language and reason over ambiguous texts supports explainable, human-aligned decisions in real time [20], when integrated with motion planning and risk assessment. However, high computational load and opaque reasoning limit practical deployment [21].

A promising direction is hybridization of rule-based systems with DRL to combine interpretability and adaptability [22, 23]. To support usability, architectures should prioritize user-centered explanations aligned with mariners' cognitive workflows [18]. Constapel et al. [12] proposed an operationalization scheme describing traffic scenarios with logical statements. Following this framework, this works encodes COLREGs encounter rules in Prolog to build a user-centered, explainable decision support system that assesses traffic, recommends actions, and provides interpretable explanations.

3. Architecture of IXDSS

IXDSS integrates situational awareness, a situational map, an explainable decision support system, and an intuitive user interface (Figure 3) to enhance maritime situational awareness and decision-making.

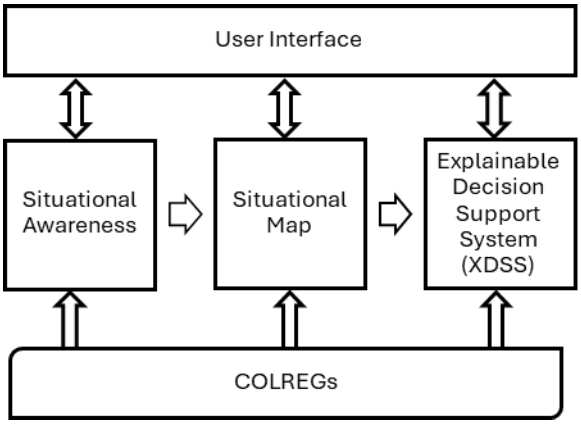

Figure 3. Architecture of IXDSS.

3.1. Situational Awareness Component

This component processes data from sensors (LiDAR, RGB, RADAR and AIS) to detect, track and perform panoptic segmentation of different ships [24]. Elements of Part C of the COLREGs (lights and shapes) can be utilized to identify vessel types and statuses in low-visibility conditions. This helps detect varied traffic situations and provides clear, explainable information to the ship's command. In the broader project[2], these sensors have been integrated into a single sensor box. However, in this paper, AIS messages are processed to extract the current traffic scenario.

The situational awareness component filters real-time AIS messages based on their distance from the Own Ship (equipped with IXDSS). Since COLREGs define "in sight" through visual observation rather than a fixed range, the AIS filter distance is user-defined to approximate clear-weather visibility. Filtered messages are analyzed to extract key static and dynamic vessel data, such as position, speed, course, heading, type, and status. Then vessels are then prioritized by their distance to the Own Ship.

[2] https://www.dfki.de/web/forschung/projekte-publikationen/projekt/xai4sfas

The system can import AIS messages from CSV or JSON files to test predefined traffic scenarios. Based on the available details, the messages undergo partial or full processing similar to real-time input. This offline mode enables case-based reasoning and helps explain IXDSS recommendations using comparable past scenarios.

3.2. Situational Map Component

The situational map component combines outputs from the situational awareness module with COLREGs rules to represent conditional truths about the current traffic scenario. It uses Prolog to encode COLREGs-based rules for traffic evaluation. Since COLREGs define only one-to-one encounters, the model encodes only pairwise relations as Prolog predicates. In scenarios with multiple encounters, each is evaluated independently. Table 1 lists the Prolog predicates describing relationships between the Own Ship ("O") and other vessels ("V"), capturing relative position, sector, scene, movement, navigation status, and passage status.

Table 1. List of Prolog Predicates used for formulating relations between Own Ship (denoted as "O") and other vessels (denoted as "V") for Situational Map.

Category	Predicate
Sector	is_ahead_of (V, O)
	is_astern_of (V, O)
	is_on_starboard_of(V, O)
	is_on_port_of(V, O)
Scene	is_in_front_of(V, O)
	is_rear_of (V, O
	is_reciprocal_to(V, O)
	is_aligned_to(V, O)
Movement	is_across (V, O)
	is_advancing(V, O)
	is_leaving (V, O)
	is_steady_with(V, O)
	is_inbound_to(V, O)
	is_outbound_from(V, O)
	is_fellow (V, O)
Passage	is_pass_ahead_of(V, O)
	is_pass_astern_of(V, O)
	is_pass_close_to(V, O)

Through logical inference, these predicates produce conditional truths used to assess safety and identify collision risks, such as vessel alignment or crossing paths. The situational map offers a dynamic, real-time view of the maritime environment, continuously updated as conditions change.

3.3. Explainable Decision Support System (XDSS)

Building on the situational map, the XDSS evaluates whether the Own Ship is in a safe or collision-risk scenario. In potential collision cases, it identifies the specific encounter type and provides actionable recommendations to the ship's command.

Explaining recommendations from a Prolog-based decision support system involves understanding how Prolog evaluates rules and facts. Because Prolog derives conclusions by satisfying binary facts, the reasoning behind a recommendation is inherently traceable.

Although Prolog's built-in tracing tools help developers follow rule execution, they are not suitable for end-users without programming knowledge.

A user-oriented approach is therefore needed. A DSS can pair each recommendation with clear explanations, concise COLREGs-based summaries and detailed lists of supporting situational facts. This method was implemented in IXDSS by enabling the system to infer all possible conclusions from current situational data. Instead of Prolog's default backward chaining, the model reformulates queries to support forward-chaining inference.

The XDSS ensures transparency by recording verified predicates as facts describing the situation and using them to justify its outputs. These facts form the basis of user-friendly explanations.

To make outputs accessible, XDSS transforms Prolog facts into readable statements. Instead of showing "spd(V, X)," it presents "Vessel has a speed of X." This is achieved by defining predicates in a form closer to natural language such as has_speed_of(Vessel, X). Once verified predicates are collected during query evaluation, they are converted into explanations through simple text reordering and formatting, such as placing the subject first and removing underscores.

In addition to detailed fact-based explanations, XDSS provides summary statements tailored to each encounter situation. For example, Listing 1 contains the Prolog predicate that generates the summary explanation for a crossing situation.

Listing 1. Prolog code for generating a summary explanation for crossing situation.

```
summary_explanation(is_crossing(V, O), Explanation): -
  is_crossing(V,O),
  format(atom(Explanation),
  "Vessel ~w is a power-driven vessel crossing from the
           starboard side of vessel ~w.
          Per COLREGs Rule 15, vessel ~w must give way to
          avoid collision.", [V, O, V]).
```

This combined approach provides users with both granular factual insight and high-level summaries, supporting interpretability and trust in the system's recommendations.

3.4. User Interface

The user interface enables smooth interaction between the system and its users by providing explanations in both textual and visual formats. It allows users to review the facts supporting system recommendations and visualize "what if" scenarios and examine prototypical examples. The combination of interactive visuals, detailed situation information and concise summaries makes complex information easier to interpret and act on.

By combining situational awareness, dynamic mapping, and explainable decision-making, IXDSS supports safe, efficient maritime navigation while ensuring transparency and trust.

4. Evaluation of IXDSS

Current literature lacks an objective method for quantifying the extent to which a DSS complies with COLREGs [25]. Although the rules provide guidance for various situations, they are intentionally broad to account for human judgment in navigation. As a result, no scoring system or numerical metric exists to assess how well a DSS aligns with the intent of the regulations. Compliance is therefore evaluated in binary terms, such as whether a collision was avoided, an encounter situation was correctly identified, or the give-way or stand-on obligations were fulfilled.

4.1. Experimental Setup and Test Scenarios

Pedersen et al. [26] proposed a software package that uses a binary-compliance approach to generate traffic-encounter scenarios for evaluating adherence to COLREGs. They also introduced a standardized set of 55 ship-encounter situations covering rules 2, 8, 13, 14, 15, 16, and 17. They are designed to represent realistic one-to-one and one-to-many cases and selected using historical traffic analyses, navigator interviews, and assessments of rule interactions [26].

IXDSS detects five encounter types, which are head-on, crossing, being crossed, overtaking, and being overtaken, corresponding to HO, CR-SO, CR-GW, TO-GW, and TO-SO in [26].

Environmental-observation uncertainty is modeled with two parameters: $\varepsilon_s \geq 0$ for sector-related facts (Figure 2b) and $\varepsilon_m \geq 0$ for movement-related facts. These can be set via sensor calibration or alternative methods (e.g., type-2 fuzzy sets). For evaluation, both parameters were set to 0.

Although IXDSS is implemented with Prolog's backward chaining, forward chaining is preferable for real-time detection in dynamic settings. Therefore, both approaches were evaluated. In backward chaining, the hypothesis is the encounter situation stated for each standardized scenario.

For evaluation, queries were derived from the scenario-file titles describing interactions between the Own Ship and Target Ships. Each traffic situation yields a single hypothesis that IXDSS validates using static and dynamic data for the ship pair, considering both perspectives (Own-Ship and Target-Ship). For example, if the Own Ship is crossing the Target Ship, the paired hypotheses are (i) Own crosses Target and (ii) Target is being crossed by Own.

In the forward-chaining evaluation, all non-conflicting encounter conclusions between a ship pair are inferred from the Own-Ship perspective and compared with the scenario title. Exactly one inferred situation must match the designated title to count as correct.

Accuracy/compliance is computed as the proportion of verified hypotheses or correct conclusions over all scenarios.

4.2. Optimal Ahead Sector Angle

There is no explicit definition of the ahead-sector angle in COLREGs [12]. In IXDSS, angles within 10° on either side of the centerline are used, consistent with navigator training and practical seamanship [12]. In contrast, [26] adopts a narrower 5° range for head-on situations when generating baseline test scenarios.

The first set of experiments aims to determine the optimal ahead-sector angle for the test scenarios by evaluating IXDSS's classification accuracy across different angles. The tested range spans 4° to 12° in 0.25° increments, with both ε_m and ε_s set to 0.

Figure 4 shows that backward inference achieves 100% accuracy for angles between 7.25° and 8.75°, while forward chaining reaches 99% accuracy between 7.25° and 8.25°. The slight advantage of backward chaining results from its use of both ship perspectives. The only undetected case in forward chaining (traffic_situation_47.json) occurs because, within the optimal angle range, the Target Ship lies in the Own Ship's ahead sector, preventing the system from classifying the situation as crossing. But, from the Target Ship's perspective, the encounter is correctly identified as being crossed from the port side.

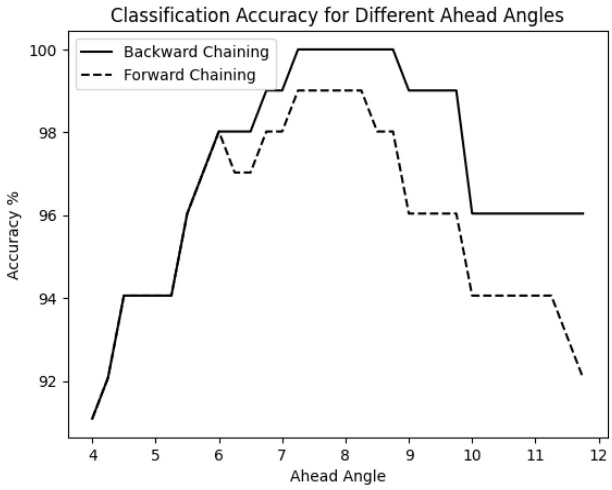

Figure 4. The optimal ahead sector angle range for backward and forward chaining.

Figures 5 and 6 illustrate that decreasing the ahead angle below the optimal range leads to missed head-on detections, while increasing it above the range causes more missed crossing and "crossed-by" cases because Target Ships fall within the ahead sector of the Own Ship.

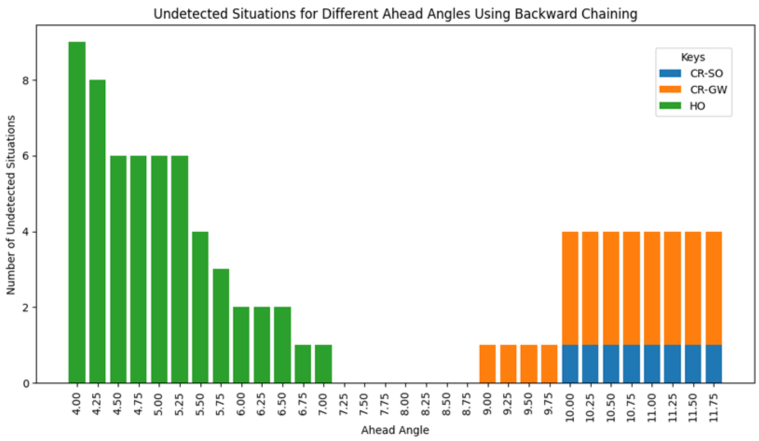

Figure 5. The optimal ahead sector angle range for backward chaining.

4.3. Robustness Against Design Parameters

In another set of experiments, the robustness of IXDSS to variations in the design parameters ε_s and ε_m was evaluated by measuring how changes in these parameters affect the accuracy of encounter-situation detection. Figure 7 presents the forward-chaining results as a heatmap over a range of ε_s and ε_m values. Backward-chaining results are not shown because that approach verifies only the goal hypothesis and does not account for contradictory conclusions. The heatmap indicates that IXDSS achieves 100% accuracy for ε_s values between 2° and 5° and ε_m values between 0 and 4.5. Outside this range, misclassification becomes more likely because situations may satisfy multiple encounter-situation classes.

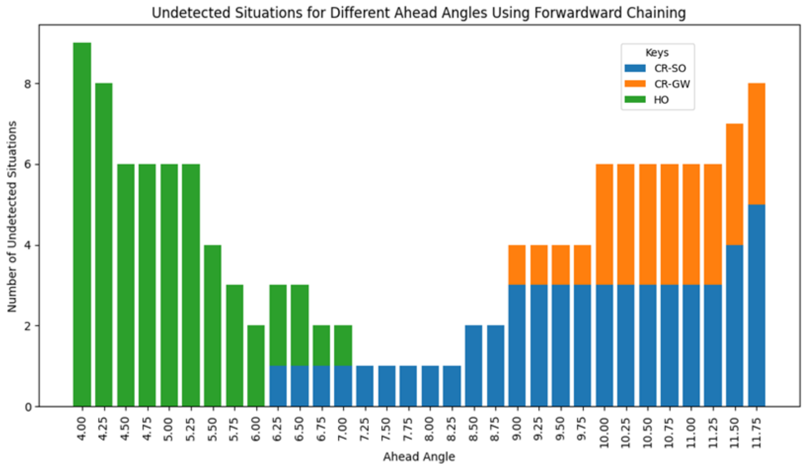

Figure 6. The optimal ahead sector angle range for forward chaining.

It is worth noting that robustness to changes in ε_s and ε_m depends not only on IXDSS but also on the characteristics of the test scenarios. Nevertheless, with these configuration settings, IXDSS achieves 100% compliance with COLREGs in the standardized traffic scenarios, correctly identifying all 101 encounter-situation pairs using complete and consistent input data.

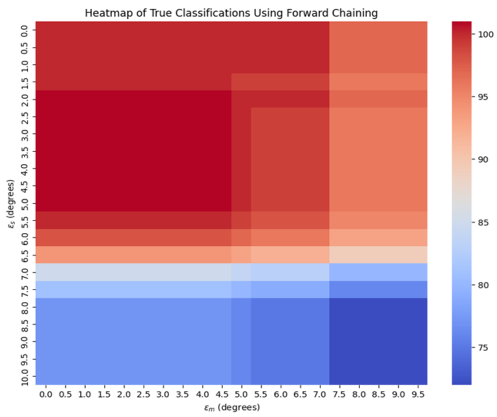

Figure 7. The relation between correct classifications of encounter situations and chang-es in εs and εm.

4.4. Explainability Evaluation

IXDSS provides multiple forms of textual explanations alongside each recommendation. For any detected situation, the system supplies a recommendation (e.g., stand on or give way) and allows users to choose among Summary, Detailed, and Fact-based explanations, as illustrated in Table 2. Table 3 further presents the supporting information extracted from the current scenario for the head-on case, based on JSON input for both the Own Ship and the Target Ship.

Table 2. Samples of different forms of textual explanations can be provided by IXDSS

Situation	Summary	Detailed	Facts
Head-on	Head-on situation as per COLREGs Rule 14: Vessel 257847600 and vessel target_ship are on reciprocal or nearly reciprocal courses and should take action to avoid collision.	Vessel 257847600 and vessel target_ship are both power-driven and on reciprocal courses, facing each other head-on. As per COLREGs Rule 14, both should alter their course to avoid collision.	257847600 is ahead of target_ship, 257847600 is visible to target_ship, 257847600 is facing target_ship, 257847600 is in front of target_ship, 257847600 is reciprocal to target_ship, 257847600 is across target_ship, 257847600 is steady with target_ship, 257847600 is inbound to target_ship, 257847600 is pass close to target_ship, 257847600 is threatening target_ship 257847600 is headon target_ship
Crossed by, Give way	Crossing situation as per COLREGs Rule 15: Vessel 257847600 is being crossed by vessel target_ship, from the port side. Vessel 257847600 must give way to vessel target_ship.	Vessel 257847600 is being crossed by vessel target_ship_1, target_ship and 257847600 are power-driven vessels, target_ship is threatening 257847600 and target_ship is on the port side of 257847600. According to COLREGs Rule 15, vessel 257847600 must take action to give way and avoid collision.	257847600 is on port of target_ship, 257847600 is visible to target_ship, 257847600 is in front of target_ship, 257847600 is across target_ship, 257847600 is advancing target_ship, 257847600 is steady with target_ship, 257847600 is inbound to target_ship, 257847600 is pass ahead of target_ship 257847600 is pass close to target_ship, 257847600 is threatening target_ship, 257847600 is crossed by target_ship
Crossing, Stand on	Crossing situation as per COLREGs Rule 15: Vessel 257847600 is approaching from the starboard side of vessel target_ship and target_ship should give way.	Vessel 257847600 is a power-driven vessel crossing from the starboard side of vessel target_ship, which is a power_driven vessel. 257847600 is threanering target_ship. Per COLREGs Rule 15, vessel target_ship must give way to avoid collision.	257847600is on starboard of target_ship, 257847600 is visible to target_ship, 257847600 is in front of target_ship, 257847600 is across target_ship, 257847600 is advancing target_ship, 257847600 is steady with target_ship, 257847600 is inbound to target_ship, 257847600 is pass ahead of target_ship, 257847600 is pass close to target_ship, 257847600 is threatening target_ship, 257847600 is crossing target_ship
Overtaking, Give way	Overtaking situation as per COLREGs Rule 13: Vessel 257847600 is approaching from behind target_ship, and 257847600 must keep clear of target_ship.	Vessel 257847600 is approaching vessel target_ship from astern and is not moving away. According to COLREGs Rule 13, vessel 257847600 is overtaking and must keep clear of vessel target_ship.	257847600 is astern of target_ship, 257847600 is visible to target_ship, 257847600 is rear of target_ship, 257847600 is across target_ship, 257847600 is advancing target_ship, 257847600 is steady with target_ship, 257847600 is inbound to target_ship, 257847600 is pass ahead of target_ship, 257847600 is pass close to target_ship, 257847600 is overtaking target_ship

These examples show how logic-programming-based explanations can enhance Human Agreement (HA) [27] by aligning system outputs with human reasoning. Summary and Detailed explanations remain transparent by clearly reflecting the logical rules that govern the detected situation. For instance, in the head-on case, the detailed explanation highlights that both ships are power-driven and on reciprocal courses, i.e. an interpretation directly derived from the predicates used to classify the encounter. Presenting situational facts also supports contextual abductive reasoning, producing verifiable explanations that reduce ambiguity and foster trust. However, providing the full list of extracted facts may overwhelm inexperienced users, who may find it difficult to distinguish relevant from irrelevant information.

Table 3. Supporting Information provided by IXDSS for the head-on situation of Table 2.

Supporting Information
Vessel 257847600 has a bearing of 1.99 degrees relative to Vessel target_ship, moving at 10.0 knots, heading of 0.0 and course over ground of 0.0. Target_ship's bearing is -1.13 degrees, moving at 12.1 knots, heading of 18.

Fuzzy parameters such as ε_m and ε_s can further complicate interpretation for inexperienced users, as they may introduce uncertainty and occasionally produce contradictory facts (e.g., a vessel simultaneously appearing in multiple sectors). Despite these inconsistencies, IXDSS generally identifies the correct situation by incorporating additional contextual information. However, exposing the full underlying facts set in such cases may offer limited benefit.

A small-scale user study was undertaken to evaluate the effects of various explanation types on trust in an AI-based recommendation system. Participants were seventeen university students who were novice users in maritime navigation tools. The evaluation was guided by three research questions addressing (1) overall trust in the system's recommendations, (2) trust in recommendations presented without explanatory information, and (3) the perceived impact of specific explanation features on user trust.

The results indicate that, overall, participants showed a baseline level of trust in the AI system's recommendations. However, when recommendations were presented without any accompanying explanation, 59% of participants reported a decrease in trust, as shown in Figure 8.

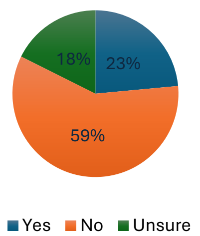

Figure 8. Participant trust in recommendations without explanatory explanations.

In general, the inclusion of explanatory information either increased user trust or had no observable effect as in Figure 9. No negative impact on trust was reported for most explanation types. An exception was observed in the case of counterfactual explanations, which in some cases led to a reduction in trust. This effect may be attributed to the presentation of alternative recommendations for similar situations, which participants may have perceived as inconsistency in the system's decision-making process.

Overall, IXDSS provides flexible explanatory options that users can select based on their needs. These explanations are transparent, cognitively aligned, and effective in illustrating the logical basis of system decisions. However, presenting all explanations is not always useful for novice users.

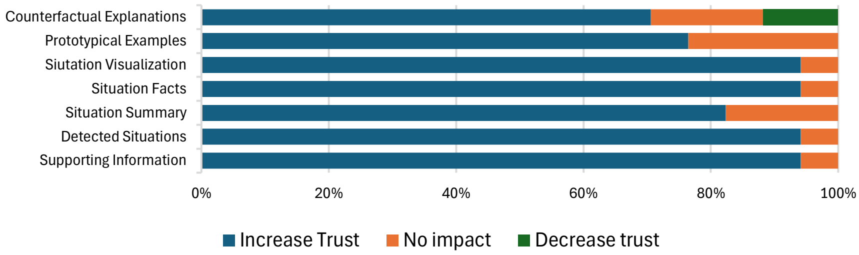

Figure 9. Impact of Different Explanation Types on Reported Trust in system Recommendations.

5. Conclusion and Future Work

The results of this work highlight the potential of logic programming to enhance maritime safety by providing decision support that is both compliant with regulations and comprehensible to operators. This represents a step toward more intelligent and explainable maritime-navigation systems with safer, technology-supported operations.

The evaluation of IXDSS across a standardized set of encounter scenarios demonstrates full compliance with COLREGs. However, the assessment also exposes several limitations in the dataset proposed in [26]. Only 101 scenarios contain complete information, revealing gaps in the test set. Moreover, because all scenarios use a single Own Ship with identical characteristics, the dataset lacks the diversity of ship types and statuses required to properly evaluate ranking rules under COLREGs. The scenarios also omit variations between heading and course-over-ground, limiting the ability to study their influence on traffic-situation detection. An experiment conducted with the Explainable Boosting Machine (EBM) [28] shows that the Own Ship's features add little to situation prediction because of their limited variability.

These findings underscore the need for a more comprehensive and varied dataset to support robust evaluation. A promising direction for future work is the development of a 2D simulation tool capable of generating encounter-situation datasets along with associated explanations, similar to the approach in [29].

IXDSS demonstrates full compliance in scenario prediction and offers adaptable explanation mechanisms to user needs, conveying decision logic. Nevertheless, evaluations indicate that detailed explanations for novice users may not always add value to trust in the system.

Acknowledgments. This study was funded by the German Federal Ministry of Research, Technology and Space (grant number 01IS23051B).

References

[1] Moreira MWL, Rodrigues JJPC, Korotaev V, Al-Muhtadi J, Kumar N. A Comprehensive Review on Smart Decision Support Systems for Health Care. IEEE Systems Journal. 2019 Sep;13(3):3536–45. doi:10.1109/JSYST.2018.2890121

[2] Cerqueti R, Maggi M, Riccioni J. Statistical methods for decision support systems in finance: how Benford's law predicts financial risk. Ann Oper Res. 2024 Nov;342(3):1445–69. doi:10.1007/s10479-022-04742-z

[3] Soori M, Jough FKG, Dastres R, Arezoo B. AI-Based Decision Support Systems in Industry 4.0, A Review. Journal of Economy and Technology. 2024 Aug;S2949948824000374. doi:10.1016/j.ject.2024.08.005

[4] Nolle L, Stahl F, El-Mihoub T. On Explanations for Hybrid Artificial Intelligence. In: Bramer M, Stahl F, editors. Artificial Intelligence XL. Cham: Springer Nature Switzerland; 2023. p. 3–15.

[5] Coussement K, Abedin MZ, Kraus M, Maldonado S, Topuz K. Explainable AI for enhanced decision-making. Decision Support Systems. 2024;184:114276. doi:https://doi.org/10.1016/j.dss.2024.114276

[6] Kirsty M. Lynch SR Victoria A Banks, Aaron PJ Roberts, Plant KL. What factors may influence decision-making in the operation of Maritime autonomous surface ships? A systematic review. Theoretical Issues in Ergonomics Science. 2024;25(1):98–142. doi:10.1080/1463922X.2022.2152900

[7] Lynch KM, Banks VA, Roberts APJ, Plant KL. (2024). What factors may influence decision-making in the operation of maritime autonomous surface ships? A systematic review. Theoretical Issues in Ergonomics Science, 25(1), 98–142. https://doi.org/10.1080/1463922X.2022.2152900

[8] Liao QV, Varshney KR. Human-Centered Explainable AI (XAI): From Algorithms to User Experiences. arXiv; 2022. Available from: http://arxiv.org/abs/2110.10790

[9] Philippakis AS. Structured what if analysis in DSS models. In: [1988] Proceedings of the Twenty-First Annual Hawaii International Conference on System Sciences. Volume III: Decision Support and Knowledge Based Systems Track . Kailua-Kona, HI, USA: IEEE Comput. Soc. Press; 1988. p. 366–70. Available from: http://ieeexplore.ieee.org/document/11929/ doi:10.1109/HICSS.1988.11929

[10] Akdağ M, Solnør P, Johansen TA. Collaborative collision avoidance for Maritime Autonomous Surface Ships: A review. Ocean Engineering. 2022 Apr;250:110920. doi:10.1016/j.oceaneng.2022.110920

[11] Chae CJ. MASS and IMO Works. In: Chae CJ, Baumler R, editors. Maritime Autonomous Surface Ships (MASS) - Regulation, Technology, and Policy . Cham: Springer Nature Switzerland; 2024. p. 9–27. (WMU Studies in Maritime Affairs). Available from: https://link.springer.com/10.1007/978-3-031-69437-0_2 doi:10.1007/978-3-031-69437-0_2

[12] Constapel M, Koch P, Burmeister HC. On the implementation of a rule-based system to perform assessment of COLREGs onboard maritime autonomous surface ships. J Phys: Conf Ser. 2022 Jul 1;2311(1):012033. doi:10.1088/1742-6596/2311/1/012033

[13] Lloyd's Register. COLREGs-International Regulations for Preventing Collisions at Sea. Rulefinder 2005, Version 9.4. 2005:1–74. Available from: https://pdf4pro.com/view/colregs-international-regulations-for-preventing-600990.html

[14] Tetreault BJ. Use of the Automatic Identification System (AIS) for Maritime Domain Awareness (MDA). In: Proceedings of OCEANS 2005 MTS/IEEE . Washington, DC, USA: IEEE; 2005. p. 1–5. Available from: http://ieeexplore.ieee.org/document/1639983/ doi:10.1109/OCEANS.2005.1639983

[15] Bakdi A, Vanem E. Fullest COLREGs Evaluation Using Fuzzy Logic for Collaborative Decision-Making Analysis of Autonomous Ships in Complex Situations. IEEE Trans Intell Transport Syst. 2022 Oct;23(10):18433–45. doi:10.1109/TITS.2022.3151826

[16] Woo J, Kim N. Collision avoidance for an unmanned surface vehicle using deep reinforcement learning. Ocean Engineering. 2020 Mar;199:107001. doi:10.1016/j.oceaneng.2020.107001

[17] Hu L, Hu H, Naeem W, Wang Z. A review on COLREGs-compliant navigation of autonomous surface vehicles: From traditional to learning-based approaches. Journal of Automation and Intelligence. 2022 Dec;1(1):100003. doi:10.1016/j.jai.2022.100003

[18] Rutledal D, Relling T, Resnes T. It's not all about the COLREGs: a case-based risk study for autonomous coastal ferries. IOP Conf Ser: Mater Sci Eng. 2020 Nov 1;929(1):012016. doi:10.1088/1757-899X/929/1/012016

[19] Madsen AN, Kim TE. A state-of-the-art review of AI decision transparency for autonomous shipping. Journal of International Maritime Safety, Environmental Affairs, and Shipping. 2024 Apr 2;8(1–2):2336751. doi:10.1080/25725084.2024.2336751

[20] Agyei K, Sarhadi P, Naeem W. Large Language Model-based Decision-making for COLREGs and the Control of Autonomous Surface Vehicles. arXiv; 2024. Available from: https://arxiv.org/abs/2411.16587 doi:10.48550/ARXIV.2411.16587

[21] Shleifer S, Rush AM. Pre-trained Summarization Distillation. arXiv; 2020. Available from: http://arxiv.org/abs/2010.13002 doi:10.48550/arXiv.2010.13002

[22] Wang C, Zhang X, Yang Z, Bashir M, Lee K. Collision avoidance for autonomous ship using deep reinforcement learning and prior-knowledge-based approximate representation. Front Mar Sci. 2023 Jan 19;9:1084763. doi:10.3389/fmars.2022.1084763

[23] Zheng K, Zhang X, Wang C, Li Y, Cui J, Jiang L. Adaptive collision avoidance decisions in autonomous ship encounter scenarios through rule-guided vision supervised learning. Ocean Engineering. 2024 Apr;297:117096. doi:10.1016/j.oceaneng.2024.117096

[24] Lejman A, Rüssmeier N, Ferdinand1 O, Stahl F. Eine integrierte Datenstromverarbeitung zur Erfassung von Umweltlagebildern. In: 22. GMA/ITG-Fachtagung Sensoren und Messsysteme 2024. GMA/ITG-Fachtagung (GMA/ITG), Nürnberg, Germany, Copernicus Publications, 2024, pp.499 - 504

[25] Woerner K. Multi-contact protocol-constrained collision avoidance for autonomous marine vehicles. PhD thesis. Cambridge, MA: Massachusetts Institute of Technology, Department of Mechanical Engineering; 2016. Available from: https://dspace.mit.edu/handle/1721.1/104118

[26] Pedersen TA, Vasanthan C, Karolius K, Engelhardtsen Ø, Houweling KP, Jørgensen A. Generating Structured Set of Encounters for Verifying Automated Collision and Grounding Avoidance Systems. J Phys: Conf Ser. 2023 Oct 1;2618(1):012013. doi:10.1088/1742-6596/2618/1/012013

[27] Mersha MA, Yigezu MG, Shakil H, AlShami AK, Byun S, Kalita J. A Unified Framework with Novel Metrics for Evaluating the Effectiveness of XAI Techniques in LLMs. arXiv; 2025. Available from: http://arxiv.org/abs/2503.05050 doi:10.48550/arXiv.2503.05050

[28] El-Mihoub TA, Nolle L, Stahl F. Explainable Boosting Machines for Network Intrusion Detection with Features Reduction. In: Bramer M, Stahl F, editors. Artificial Intelligence XXXIX. Cham: Springer International Publishing; 2022. p. 280–94. (Lecture Notes in Computer Science). Available from: https://link.springer.com/10.1007/978-3-031-21441-7_20 doi:10.1007/978-3-031-21441-7_20

[29] Elsayed AH, El-Mihoub TA, Manss C, Miedtank A, Nolle L, Stahl F. Interactive Simulator Framework for XAI Applications in Aquatic Environments. In: Bramer M, Stahl F, editors. Artificial Intelligence XLI. Cham: Springer Nature Switzerland; 2025. p. 144–57. (Lecture Notes in Computer Science). Available from: https://link.springer.com/10.1007/978-3-031-77915-2_11 doi:10.1007/978-3-031-77915-2_11