Journal of Marine Science and Technology, Vol. 27, No. 1, pp. 1-7 (2019)
DOI: 10.6119/JMST.201902_27(1).0001

A STUDY ON SEAWORTHINESS OF THE KINMEN-XIAMEN FAIRWAYS BY FUZZY METHOD

Chien-Min Su[1]*, Ki-Yin Chang[2]*, Sheng-Long Kao[1]*, and Chuan Lin[1]

Key words: fairway planning, fuzzy distinction, fairway membership index, Marine Geographic Information System (MGIS), electronic chart system (ECS).

ABSTRACT

In recent years, more than five times as many ships have been crossing the Kinmen-Xiamen fairways as did ten years ago. For this traffic, plans of the once war-torn fairways are only available on charts. However, the nautical charts of the area show that information regarding tidal changes and environment is incomplete. In particular, some current fairways that have not been planned or corrected pass through suspected minefields. In fact, vessels sailing these waters do not navigate on the originally planned fairways, resulting in heavy, complicated vessel traffic and highlighting the need to investigate fairway seaworthiness. This study used long-term information received from the Automatic Identification System (AIS) regarding vessels passing through the Kinmen-Xiamen fairways. The data was then entered into the Marine Geographic Information System (MGIS), through which vessel location information is shown in the electronic chart system (ECS). The linguistic variables of vessel draft vessel traffic density, and distance from original fairway were taken as inputs for fuzzy logic control. The fairway membership index, acquired via the fuzzy distinction method, was employed to evaluate spatial planning analysis. A novel method is proposed to determine the seaworthiness and safety of a fairway, for reference in future fairway planning.

I. INTRODUCTION

The implementation of the mini three links for the Kinmen-Xiamen area calls for a sea safety route. Although the route has been planned, there are concerns about convenience and safety due to the changing hydrological environment, the accuracy of sea charts, tidal conditions, watercraft congestion, and overlapping unmarked minefields (Tsai and Chiang, 2014).

Under these circumstances, the navigation aids that were originally planned for the Kinmen-Xiamen sea route are either insufficient or incapable to be used for navigational reference. This poses a high risk of collision between ships, makes it difficult to attribute responsibility if mishaps do occur, and puts people and property at risk. In addition, while changes in cross-strait relation have led to unmarked minefields in the Kinmen-Xiamen area being gradually removed (Chen, 2010), concerns about the efficacy and safety of the existing sea route remain.

A traditional fairway plan is based on vessel draft and hazardous obstacles (Chen et al., 2015; Chou et al., 2015). In this study, three linguistic variables, vessel draft, vessel traffic density, and distance from original fairway, were taken as inputs for fuzzy logic control (FLC). The output, fairway membership index (FMI), can be used in the Marine Geographic Information System (MGIS) to decide the seaworthiness of fairways in which vessels have sailed safely at a vessel draft of at least 10 meters over the past twelvemonths. Previous studies, both domestic and foreign, have probed nautical issues using the fuzzy method (Pietrzykowski and Uchacz, 2003; Pietrzykowski, 2008). The scholars used the Vessel Traffic Service (VTS) to apply speed, sea condition and ship length as fuzzy linguistic variables, establishing a VTS collision avoidance alert system that functions upon receiving the radius of the fuzzy guarding ring after defuzzification (Kao et al., 2007). Later, they also integrated fuzzy theory with MGIS, setting ship length, speed and distance as linguistic variables and finding that applying danger alert values to signals facilitated decision-making in collision avoidance (Kao et al., 2013).

Although a plethora of studies have suggested the application of fuzzy theory to navigation, studies about the application of fuzzy theory to fairway planning remain scanty. To investigate such feasibility and to resolve fairway issues within the Kinmen-Xiamen fairways, this study adopts the linguistic variable defuzzification model and integrates fuzzy theory with MGIS (Kao et al., 2013). Vessel traffic density analysis and the fuzzy distinction method are used to display a ship's AIS (Automatic Identification System) location via MGIS, with the data later

Paper submitted 01/10/18; revised 06/22/18; accepted 09/01/18. Author for correspondence: Ki-Yin Chang (e-mail: b0170@mail.ntou.edu.tw).
[1] Department of Transportation Science, National Taiwan Ocean University, Taiwan, R.O.C.
[2] Department of Merchant Marine, National Taiwan Ocean University, Taiwan, R.O.C.
[*] Center of Excellence for Ocean Engineering

converted into vessel traffic density. With a comparison against the fairway suggested by the existing nautical chart 0319A and with subsequent fuzzy distinction, it is hoped that seaworthiness fairway planning can be optimized.

II. BASIC RESEARCH METHOD

1. AIS and MGIS Integration System

According to the IMO and Chapter V, Regulation 19 of the International Convention for the Safety of Life at Sea (SOLAS), all ships of 300 gross tonnage and above engaged on international voyages; cargo ships of 500 gross tonnage and above not engaged on international voyages; and all passenger ships, irrespective of size, shall be fitted with AIS (IMO, 2002; Robards et al., 2013). To improve vessel navigational security and message transmission, the International Association of Lighthouse Authorities (IALA) and the International Telecommunication Union (ITU) have established related requirements and regulations regarding AIS equipment specifications, regulations, installation and usage (IALA, 2011). AIS can effectively and rapidly provide navigational security information between ships and from ship to shore, assisting maritime authorities in monitoring vessel activity within an area in order to avoid vessel collision and grounding. The purpose of the installation of AIS by vessels is to transmit messages to other vessels and receive messages from them. As a result, vessels may continuously transmit important navigational information between each other and receive static and dynamic information from surrounding vessels. Significant data includes ship registration, ship location, navigational course, speed, direction, and rate of turn.

A Geographic Information System (GIS) uses computer hardware and software to process geographic information and store it in a database. Analysis and simulation functions in the software transform geographic data into meaningful information that aids decision-making and planning (Jankowski, 1995; Martin, 2003). The application of the tools, methods or concepts of GIS processing to the analysis and display of marine-related information is referred to as the "Marine Geographic Information System" (MGIS). MGIS is a tool for integrating the collection, management, analysis, simulation, presentation, and prediction of all kinds of spatial data relevant to the marine world. It mainly uses map overlay and spatial analysis functions to convert original geographic data into digital data. Computer systems are used to display spatial conditions and to provide useful information for spatial planning. In this study, ArcGIS 10.1 GIS software was employed to construct a MGIS database for retrieving data, models and knowledge criteria.

This study has successfully integrated AIS and MGIS via MS Visual Studio, using AIS/MGIS interface parsing to convert vessel information received by AIS into information for MGIS (as shown in Fig. 1). With AIS/MGIS interface parsing, information originally received by AIS has been converted into useful vessel information, such as MMSI, latitude and longitude, and course. Vessel activities could be presented on the MGIS platform, thus realizing the purpose of monitoring vessels.

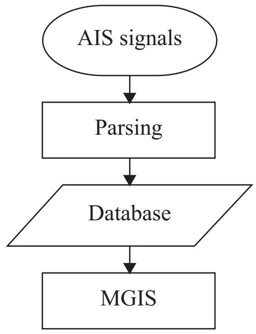

Fig. 1. Integration flowchart of AIS and MGIS.

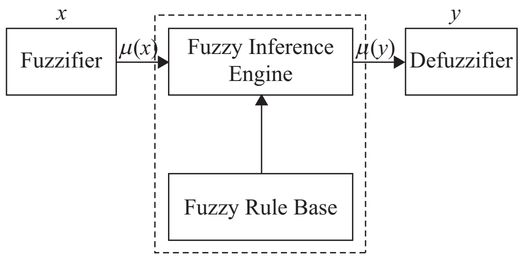

Fig. 2. Basic framework of a fuzzy control system.

2. Fuzzy Theory

Fuzzy theory was first proposed in 1965 (Zadeh, 1965). Since then, numerous studies have been conducted in this field. Fuzzy theory has been widely applied to various disciplines in the natural and social sciences. It was developed to resolve "fuzzy" concepts existing in the real world that cannot be clearly defined or described by mathematical methods (Zadeh, 1997). It is particularly effective in representing linguistic fuzziness in human language. Generally, the basic framework of a fuzzy control system includes (1) a fuzzifier, (2) a fuzzy rule base, (3) a fuzzy inference engine and (4) a defuzzifier (as shown in Fig. 2). The fuzzifier function converts information into optimal fuzzy linguistic information; the fuzzy rule base consists of the knowledge and rules collected from expert experience and opinions in order to resolve related issues; the fuzzy inference engine may be seen as the core of the fuzzy system, applying approximate reasoning or fuzzy inference methods to simulate human decision-making processes and resolve the issues at hand; finally, the defuzzifier converts a linguistic conclusion into a realistically quantifiable value that represents the fuzzy value of the optimal linguistic output variable, for the purpose of controlling and decision-making.

III. RESEARCH PROCEDURES

In order to investigate the seaworthiness of the Kinmen-Xiamen fairways, marine information on the Kinmen-Xiamen mini three links was collected for reference and nautical charts were selected and digitized. AIS receivers were set up around the Kinmen area to receive various long-term information regarding passenger and commercial ships crossing the mini three links. The latitudes and longitudes of the ships' positions were organized and imported into the MGIS system, where vessel traffic density was analyzed with the density function. The resulting information was then overlapped onto the ECS, course and density features through the map overlay function in order to evaluate the seaworthiness of planned fairways on current nautical charts. Finally, the FMI output was acquired using the fuzzy distinction method, in an attempt to verify the seaworthiness of the original fairways and in order to propose new methods for fairway planning. The research procedures of the current study were as follows:

(1) Collecting information on the Kinmen-Xiamen fairways
Collecting information on the Kinmen-Xiamen fairways, including appropriately scaled nautical charts, vessel draft, topography, navigation aid facilities, and original fairways.
(2) Receiving and organizing AIS data
Receiving long-term AIS data for ships and decoding it into MGIS readable files using the integrated AIS and MGIS system.
(3) Density analysis
Importing vessel location points into ECS and generating density features using the density function in ArcGIS.
(4) Seaworthiness evaluation
Overlaying the generated density features on existing fairways in the ECS and comparing them, for the purpose of evaluating fairway seaworthiness.
(5) Fuzzy distinction
Conducting fuzzy distinction on vessel draft, vessel traffic density, and distance from the original fairway, for the purpose of verifying the seaworthiness of the originally planned fairways on the nautical charts.

IV. IMPLEMENTATION RESULTS

1. Choice and Digitization of Nautical Chart

The digitization of nautical chart 0319A was performed via ArcGIS. The ECS was meshed for fuzzy distinction, as shown in Fig. 3.

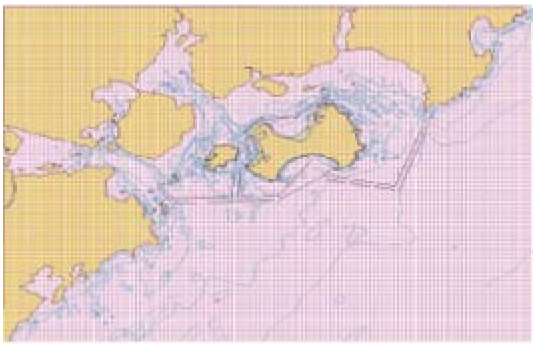

Fig. 3. Raster of nautical chart.

2. Density Analysis

Density analysis was performed using the spatial analysis density function in ArcGIS. The collected AIS data was integrated into the ECS and converted into an excel file after coding by AIS. Twelve months of AIS data concerning vessels sailing between Kinmen and Xiamen in water at least 10 meters deep were collected and stored as twelve separate files. Taking the first file as an example, Add XY Data was used to import the Excel file, where the X column indicated the longitude (lon), the Y column indicated the latitude (lat), and the Edit setting for Description was WGS84.

The AIS-recorded vessel location may be acquired after successfully importing the data (as shown in Fig. 4). Using the spatial analysis kernel density function, 01 was the input point for the initial data, stored location was the output raster, Output cell size was set at 0.001,and Search radius was set at 0.01.

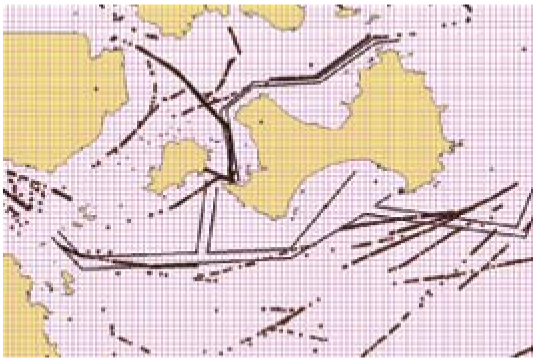

Fig. 4. Import AIS-recorded vessel location points.

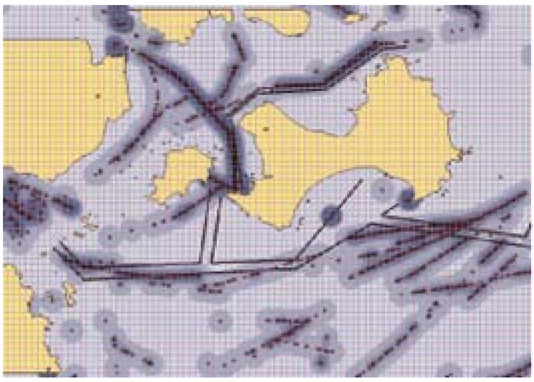

Fig. 5. Density chart yielded by spatial analysis.

This setting yielded the density features shown in Fig. 5.

Subsequently, the other 11 sets of data were similarly imported in order to process their density. All were integrated using the Data Management Tools → General → Merge function. The results are shown in Fig. 6.

3. Seaworthiness Analysis

The density layers were overlaid onto the ECS fairway layer. Vessel locations and grids were then turned off for clearer display.

The density of the fairway from Shuitou wharf to Dongdu wharf (the red line) noticeably deviated from the planned fairway and passed through suspected minefields (the yellow oval

Table 1. Input and Output of Membership Functions.

Input		
Linguistic Variable	Definition	Fuzzy Linguistic Value
Vessel draft (Depth)	Water depth information for the Kinmen-Xiamen fairways; the shallowest value is the minimum draft plus 2 m of the draft margin, while the deepest value is the deepest water of the region.	*Shallow* (10m) *Medium* (21m) *Deep* (32m)
Vessel traffic density (Density)	Twelvemonths of statistical data points for vessel traffic density, in which the highest and lowest points are data from statistical calculations.	*Low* (90,000 points) *Medium* (3,730,000 points) *High* (7,370,000 points)
Distance from original fairway (Distance)	Distance from the original fairway, shown in nautical miles; the shortest distance is 0.2 NM (Nautical mile)and the longest distance is less than 1 NM.	*Short* (0.2 NM) *Medium* (0.6 NM) *Long* (1 NM)
Output		
Linguistic Variable	Definition	Fuzzy Linguistic Value
Fairway membership index (FMI)	Used for fuzzy distinction, the numerical value is 0-1, with larger values representing a greater seaworthiness index output for fairway planning.	*Small* (0) *Medium* (0.5) *Large* (1)

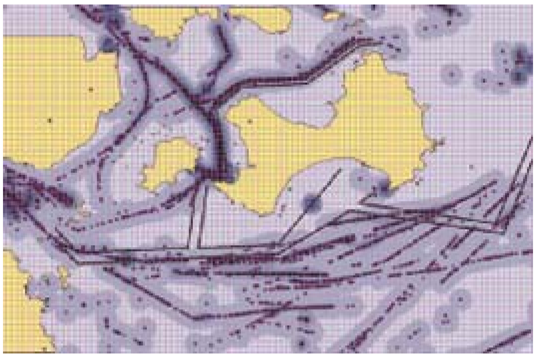

Fig. 6. Density chart of all AIS-recorded vessel location points.

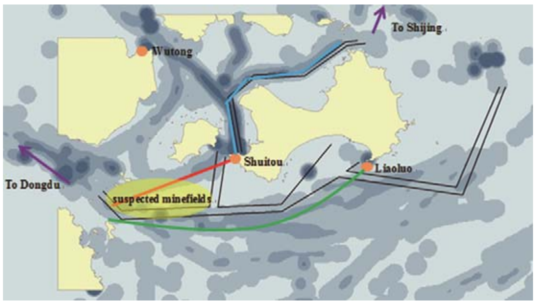

Fig. 7. Fairway layer analysis on electronic chart system.

area), as shown in Fig. 7. In addition, the density of the fairway from Liaoluo wharf to Dongdu wharf (the green line) also visibly deviated towards the south, avoiding the suspected minefields. The fairway from Shuitou wharf to Wutong wharf has yet to be planned. The density of the fairway from Shuitou wharf to Shijing wharf (the blue line) showed a slight deviation.

4. Fuzzy Distinction

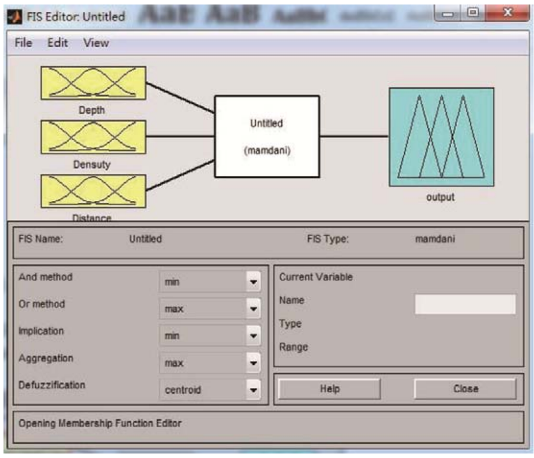

Fig. 8. Membership function input& output system.

1) Establishingthe Fuzzy Membership Function

The input linguistic variables of the fuzzy system are vessel draft (Depth), vessel traffic density (Density) and distance from the original fairway (Distance). The output linguistic variable is fairway membership index (FMI). The input and output variables are shown in Fig. 8 and Table 1.

The membership function is trigonometric, with fuzzy logic membership function in MATLAB used to select input and output functions corresponding to the trigonometric function.

The membership values were established as follows:

(1) Vessel draft (Depth)

Vessel draft data used in this study was taken from the vessel draft values marked in nautical chart 0319A of the Kinmen area. The linguistic variable was further divided into three membership functions: *Shallow*, *Medium*, and *Deep*. The membership function adopted was trigonometric, with the following linguistic set:

$$\mu_{shalow}(x)=\begin{cases}1 & for\ x\le 10\\ \dfrac{21-x}{11} & for\ 10\le x\le 21\end{cases} \quad (1)$$

$$\mu_{shalow}(x)=\begin{cases}\dfrac{x-10}{11} & for\ 10\le x\le 21\\ \dfrac{32-x}{11} & for\ 21\le x\le 32\end{cases} \quad (2)$$

$$\mu_{deep}(x)=\begin{cases}\dfrac{x-21}{11} & for\ 21\le x\le 32\\ 1 & for\ 32\le x\end{cases} \quad (3)$$

(2) Vessel traffic density (Density)
The vessel traffic density referred to the dynamic and static information about vessels received by AIS. Twelvemonths' positions of vessel-location data from the Kinmen-Xiamen area were collected. Vessel traffic flow was constructed using the Density tool, with the fuzzy input linguistic variables defined as three membership functions: *Low*, *Medium*, and *High*. The membership function adopted was trigonometric, with the following linguistic set:

$$\mu_{low}(y)=\begin{cases}1 & for\ y\le 9\\ \dfrac{32-x}{11} & for\ 9\le y\le 373\end{cases} \quad (4)$$

$$\mu_{medium}(y)=\begin{cases}\dfrac{y-9}{364} & for\ 9\le y\le 373\\ \dfrac{737-y}{364} & for\ 373\le y\le 737\end{cases} \quad (5)$$

$$\mu_{high}(y)=\begin{cases}\dfrac{y-737}{364} & for\ 373\le y\le 737\\ 1 & for\ 737\le y\end{cases} \quad (6)$$

(3) Distance from the original fairway (Distance)
As a membership function, the distance of each density area from the original fairway was obtained with the use of the GIS distance measurement tool. The linguistic variables were divided into the following three membership functions: *Short*, *Medium*, and *Long*. The membership function adopted was trigonometric, with the following linguistic set:

$$\mu_{low}(z)=\begin{cases}1 & for\ z\le 0.2\\ \dfrac{0.6-z}{0.4} & for\ 0.2\le z\le 0.6\end{cases} \quad (7)$$

$$\mu_{medium}(z)=\begin{cases}\dfrac{z-0.2}{0.2} & for\ 0.2\le z\le 0.4\\ \dfrac{1-z}{0.6} & for\ 0.4\le z\le 1\end{cases} \quad (8)$$

$$\mu_{long}(z)=\begin{cases}\dfrac{z-0.6}{0.4} & for\ 0.6\le z\le 1\\ 1 & for\ 1\le z\end{cases} \quad (9)$$

(4) Fairway membership index (FMI)
The linguistic variables of the output were divided into the following three membership functions: *Small*, *Medium*, and *Large*. The membership function adopted was trigonometric, with the following linguistic set.

$$\mu_{small}(f)=\begin{cases}1 & for\ f\le 0\\ \dfrac{0.5-f}{0.5} & for\ 0\le f\le 0.5\end{cases} \quad (10)$$

$$\mu_{medium}(f)=\begin{cases}\dfrac{f-0}{0.5} & for\ 0\le f\le 0.5\\ \dfrac{1-f}{0.5} & for\ 0.5\le f\le 1\end{cases} \quad (11)$$

$$\mu_{large}(f)=\begin{cases}\dfrac{f-0.5}{0.5} & for\ 0.5\le f\le 1\\ 1 & for\ 1\le f\end{cases} \quad (12)$$

2) Fuzzy Rule Base

In terms of fairway planning, a deeper the depth and a greater the density are better for the given position. The fuzzy rule-based database constructed according to these rules is shown in Table 2.

Table 2. Fuzzy Rules.

Value / Rule	Depth	Density	Distance	FMI
Rule1	*shallow*	*low*	*short*	*small*
Rule2	*shallow*	*medium*	*short*	*medium*
Rule3	*shallow*	*high*	*short*	*large*
Rule4	*shallow*	*low*	*medium*	*small*
Rule5	*shallow*	*medium*	*medium*	*medium*
…	…	…	…	…
Rule23	*deep*	*medium*	*medium*	*medium*
Rule24	*deep*	*high*	*medium*	*large*
Rule25	*deep*	*low*	*long*	*small*
Rule26	*deep*	*medium*	*long*	*medium*
Rule27	*deep*	*high*	*long*	*large*

3) Fuzzy Distinction in Fairway Planning

Based on the aforementioned fuzzy rule (integrated into the GIS's ECS for fuzzy distinction, with the output value rounded up to the first decimal between 0 and 1), higher values indicate

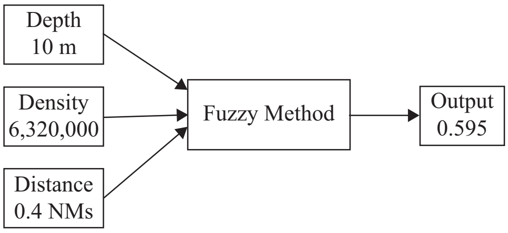

Fig. 9. Input and output of fuzzy distinction.

Fig. 10. Example of fairway fuzzy distinction with three input variables and FMI output.

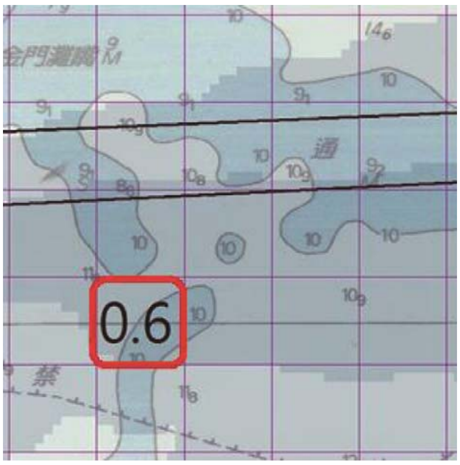

Fig. 11. Example of 0.6 (FMI value) on a gird of 5 × 5 area.

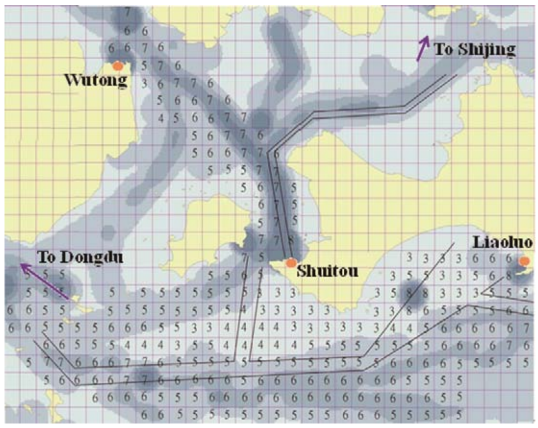

Fig. 12. Fairway membership index outputs.

better seaworthiness for fairway planning. Fig. 9 illustrates the example of a 5 × 5 area of the fairways. To obtain FMI, an example of fairway fuzzy distinction with three input variables (Depth, Density and Distance) is shown in Fig. 10.

In the grid, the vessel draft is 10 m, the density is 6,320,000 points, the distance from the original fairway is 0.4 NM, and the output value is 0.595, rounded up to 0.6 in the grid (as shown in Figs. 10 and 11). Values exceeding the average indicated an appropriate fairway seaworthiness for the area.

This study focused on the three fairways that were most problematic in terms of seaworthiness: the fairways from Shuitou wharf to Wutong wharf, from Shuitou wharf to Dongdu wharf, and from Liaoluo wharf to Dongdu wharf. For higher readability, the FMI outputs for the fairways were rounded up to the first decimal, as shown in Fig. 12 (3, 4, 5, 6, and 7 on each grid means an FMI index of 0.3, 0.4. 0.5, 0.6, and 0.7, respectively). Even though appropriate fairway planning could be identified, relatively close values led to huge fuzzy areas.

Fuzzy distinction revealed that vessel draft and vessel density have greater effects on the output value. Therefore, the FMI was correlated with the distance between the original fairway and the seaworthy fairway. Hence, the fuzzy rules were altered from “If Depth and Density and Distance” (rule A) to “If Depth and Density or Distance” (rule B)and the given areas were analyzed in terms of full-range FMI output. In Fig. 13, the values

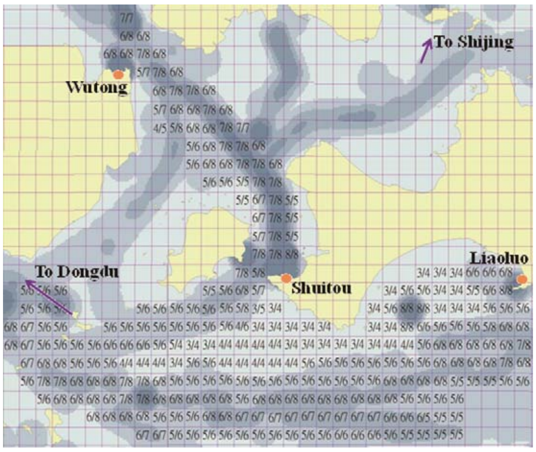

Fig. 13. Output results of the FMI change, by rule A and rule B.

on the left side of the slash follow the original rule A, and those on the right side of the slash are the corresponding values after the FMI was modified by rule B. The results indicated that the new value intervals were greater than the originals, clearly distinguishing the navigable fairway planning areas. The FMI is shown in color levels, a darker color and a greater value indicating higher fairway seaworthiness. Based on the FMI values, this study proposed the potential fairways indicated by dashed lines in Fig. 14.

The results, GIS analysis, fairway evaluation, and fuzzy distinction revealed that of the Kinmen-Xiamen mini three links, the fairway from Shuitou wharf to Shijing wharf was closest to the original one. The fairway from Shuitou wharf to Wutong wharf has yet to be completed and the potential seaworthy fairway is shown as dashed red line in Fig. 14. The fairway from Shuitou wharf to Dongdu wharf takes an even longer and more inefficient detour. In addition, vessel density results showed that most vessels chose to navigate the suspected minefields instead of following the originally planned fairway, where vessels first navigated towards the south and then took a course in the suspected minefields.

V. CONCLUSIONS

This study proposed the fairway membership index (FMI) via fuzzy distinction as a novel method for determining the seaworthiness of fairways. With regard to the major fairway from Liaoluo wharf to Dongdu wharf, the fairway crossed suspected minefields and the vessel track density showed deviation from the fairways. It is thus obvious that the planned fairways on the mini three link nautical charts do not meet actual needs. Hence, it is critically urgent to plan new fairways. Since night-time navigation has recently started, planning and management in the mini three link fairways system has become even more complicated, and navigation aid facilities are needed for assistance. Therefore, the current study utilized modern communication technologies and fuzzy spatial decision-making methods to analyze and plan the Kinmen-Xiamen fairways, specifically probing the

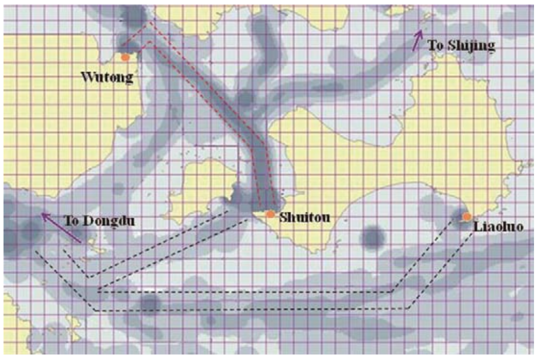

Fig. 14. Seaworthy fairway area and potential broadened fairway.

variance differences between actual needs and the planned fairways incurrent paper-based nautical charts. Fuzzy FMI analysis was proposed to assist with fairway planning for the mini three link fairways and FMI output for the entire nautical chart was created. Potential safe and seaworthy fairways (minimum 10 m vessel draft) within the Kinmen-Xiamen fairways are provided for future planning.

REFERENCES

Chen, C.-M. (2010). Role of tourism in connecting Taiwan and China: Assessing tourists' perceptions of the Kinmen-Xiamen links. Tourism Management 31, 421-424.

Chen, J., F. Lu and G. Peng (2015). A quantitative approach for delineating principal fairways of ship passages through a strait. Ocean Engineering 103, 188-197.

Chou, C. C., Y. L. Su, R. F. Li, C. L. Tsai and J. F. Ding (2015). Key navigation safety factors in taiwanese harbors and surrounding waters. Journal of Marine Science and Technology 23, 689-693.

IALA (2011). IALA Recommendation A-126 On The Use of the Automatic Identification System (AIS) in Marine Aids to Navigation Services.

IMO (2002). SOLAS Chapter V, Regulation 19.2-Carriage requirements for shipborne navigational systems and equipment.

Jankowski, P. (1995). Integrating geographical information systems and multiple criteria decision-making methods. International journal of geographical information systems 9, 251-273.

Kao, S. L., K. T. Lee, K. Y. Chang and M. D. Ko (2007). A Fuzzy Logic Method for Collision Avoidance in Vessel Traffic Service. Journal of Navigation 60, 17-31.

Kao, S. L., M. A. Lee and J. A. Hsu. (2013). Study on fuzzy virtual AToNs for marine vehicles collision avoidance, Taiwan.

Martin, D. (2003). Geographic information systems: socioeconomic applications. Taylor & Francis.

Pietrzykowski, Z. (2008). Ship's fuzzy domain-a criterion for navigational safety in narrow fairways. The Journal of Navigation 61, 499-514.

Pietrzykowski, Z. and W. Uchacz (2003). Optimisation of vessel trafic using fuzzy linear programming. Annual of Navigation, 65-79.

Robards, M. D., G. K. Silber, J. D. Adams, J. Arroyo, D. Lorenzini, K. Schwehr and J. Amos (2013). Conservation science and policy applications of the marine vessel Automatic Identification System (AIS)—a review. Bulletin of Marine Science, 92, 75-103.

Tsai, H.-M. and B.-W. Chiang (2014). Enclosing resources on the islands of Kinmen and Xiamen: From war blockade to financializing natural heritage. Journal of Marine and Island Cultures 3, 69-77.

Zadeh, L. A. (1965). Fuzzy sets. Information and Control 8, 338-353.

Zadeh, L. A. (1997). Toward a theory of fuzzy information granulation and its centrality in human reasoning and fuzzy logic. Fuzzy sets and systems 90, 111-127.