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# DEFINITION OF SINES PORT WAVE REGIME USING AN ARTMAP ARTIFICIAL NEURAL NETWORK WITH FUZZY LOGIC

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## Abstract

Techniques based on Artificial Neural Networks (ANN) have been increasingly applied to predict natural hazards. In this work, a Fuzzy ARTMAP ANN was trained to predict the wave regime at the entrance and inside the Sines Port, on the Portuguese west coast. *In situ* measurements, buoy data and results from numerical modeling were used to train and validate the ANN. The wave regime was calculated for different points outside and inside the port. This methodology proved to be able to provide a fast and satisfactory response, especially useful in the scope of forecast and warning systems.

*Keywords*: Artificial Neural Network, Fuzzy ARTMAP, Wave Regime, Sines Port.

## 1. Introduction

Wave climate characterization is an essential issue for coastal and harbor areas. These areas are socially and economically very important but also quite sensitive to natural hazards. Therefore a proper forecast of the wave climate is of upmost importance for such sensitive areas in order to avoid significant environmental and economic losses and to support coastal planning and management.

The forecast of sea waves is usually performed using various methodologies that have shown satisfactory results, which are based on empirical formulations, numerical and physical modeling. Numerical hindcast and wave propagation models represent a powerful tool to address problems in coastal engineering.

They give an important contribution in this context, due to their flexibility and wide application range. Although these models allow the easy simulation of several scenarios, they are computationally demanding and have their own limitations, since they cannot simulate all the physical phenomena involved in the complex processes of wave generation, propagation and dissipation from offshore to the coastline.

Physical modeling can analyze these phenomena but it is expensive, time consuming, requires very specific infrastructure and proper equipment and a high experience by those who perform the tests and analyze the results.

Therefore, techniques based on Artificial Neural Networks (ANN) have been taken up with great approval by their users (Londhe and Deo, 2004). These ANNs have proven to be very useful for engineering purposes but still have some limitations mainly related with the lack of generalization.

In this connection, the ARTMAP neural network named FAM, which is of the ART (Adaptive Resonance Theory) type, with Fuzzy Logic techniques, has been developed and its description is available in Santos *et al*. (2013), as well as its first application performed to determine the wave conditions at Sines Port, on the Portuguese west coast.

Following that work, the present one uses *in situ* measurements, buoy data and numerical modeling results to train and validate the ANN. *In situ* measurements were taken on the 26th February 2009 and on the 25th February 2011, at different points inside the Port of Sines. Data from the wave buoy located offshore the port were also used, from May 1988 to December 2002 and from January 2005 to June 2012. The numerical modeling results outside and inside the port were obtained by using the models SWAN (Booij *et al*., 1999) and DREAMS (Fortes, 2002), respectively.

Wave buoy data and numerical results were applied to train the FAM network. To evaluate its performance, numerical results in several points outside and inside the port were used. Finally, network results were compared with *in situ* measurements inside the port.

## 2. Study Area

The Port of Sines is located on the Southwest of Europe, more precisely on the west coast of Portugal, where the main international maritime routes meet – East-West and North-South (Figure 1).

Figure 1. Port of Sines.

Being a modern port (1978), with excellent maritime access, it is one of the major trade and economic gateways of the Iberian Peninsula, considered a port of upmost geographic and strategic importance to Portugal and Spain.

It is an open deep water sea port, sheltered by two main breakwaters (the west and the east breakwaters), which protect five main terminals: liquid bulks, petrochemical products, multipurpose, LNG and container.

Due to its modern specialized terminals, the port is able to handle the different types of cargoes, leading the Portuguese port sector in the volume of cargo (mainly bulk cargos, both liquid and solid), and offering unique natural characteristics to receive any type of vessels.

The offshore wave conditions at the Port of Sines are defined based upon data from the directional wave-buoy "Sines 1-D", which are available from *Instituto Hidrográfico*, Portugal. The buoy is located offshore the port (37º55'N and 08º55'W) at a water depth contour of -93 m (CD).

In normal conditions, the wave parameters, such as the significant wave height (HS), the peak wave period (TP) and the mean wave direction (DIR), are produced every 1 hour, based on a 30 min period of wave buoy measurements. Table 1 presents an overview of the buoy data from May 1988 to December 2002 and from January 2005 to June 2012.

Table 1. Statistical parameters at "Sines 1-D" wave buoy (data from May 1988 to December 2002 and from January 2005 to June 2012).

| | MAXIMUM | AVERAGE | MINIMUM | STANDARD DEVIATION | MORE FREQUENT |
|---|---|---|---|---|---|
| **HS (m)** | 7.35 | 1.60 | 0.27 | 0.90 | [1.00-2.00] (48.1%) |
| **TP (s)** | 19.8 | 8.8 | 4.2 | 2.3 | [6.0-7.0] (17.8%) |
| **DIR (º)** | 358 | 299 | 5 | 19 | [300–310] (32. 7%) |

## 3. Methodology

### 3.1 Outline

The training and validation of the developed FAM network with *in situ* measurements, buoy data and numerical results at the Port of Sines involved several procedures, namely:

1. Wave propagation calculations from offshore (wave buoy location) to inside the port, by using the SWAN and the DREAMS numerical models, in order to obtain the wave characteristics at several points outside and inside the port, respectively. It is important to note that the wave-buoy is located at a short distance from the port (89 m), which means that the wind effect on the wave regime can be neglected;
2. Training of the FAM network with both the wave buoy data and the numerical modeling results;
3. Comparison of the results outside the port from the FAM network and the SWAN model;
4. Comparison of the results inside the port from the FAM network and the DREAMS model;
5. Validation of the FAM results (as well as the DREAMS results) inside the port with *in situ* measurements.

The studied points outside the port (SWAN point), at the entrance (point A) and inside the port (points B to G) are those presented in Figure 2.

### 3.2 Numerical modeling of the wave propagation

The SWAN (Booij *et al*., 1999) and the DREAMS (Fortes, 2002) models were used to perform wave propagation calculations from offshore (wave buoy location) to the region outside the Port of Sines (SWAN point) and into the port (points A to G). Offshore wave conditions correspond to wave buoy measurements (37º55'N e 08º55'W) from 1988 to 2002 and from 2005 to 2012, giving a total of 51247 wave data records. The applied methodology was adopted from Neves *et al*. (2010).

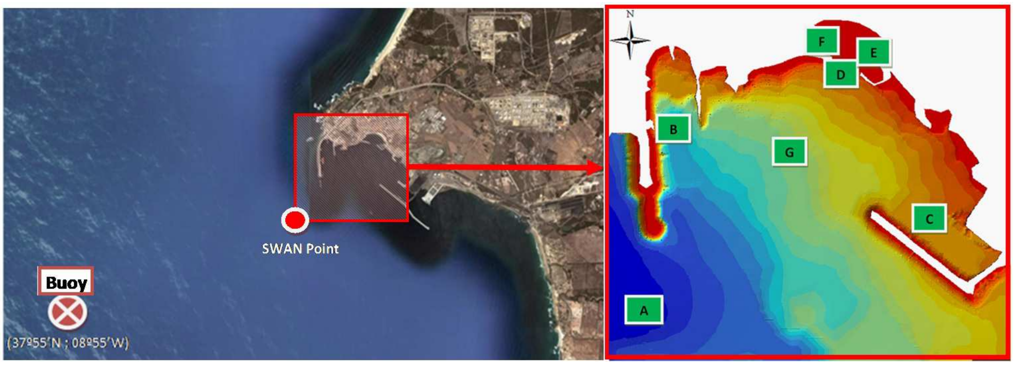


Figure 2. Studied points inside and outside the Port of Sines.

For this test case, the SWAN model was applied to propagate each offshore wave condition up to the SWAN point (Figure 3). From here, the DREAMS model was applied to propagate the predicted wave conditions to the port entrance (point A) and into the port (points B to G). Note that the need for using these two models is a consequence of their own limitations.

Within the port, the wave reflection on the port boundaries is one of the phenomena that determine the wave characteristics and that it is not properly simulated by SWAN. Thus, there is the need to use the DREAMS model, which takes into account this phenomenon, but that can only be used in small areas due to the computational effort involved.

Numerical results (in terms of HS, TP, DIR) were obtained outside and inside the port, but specifically for the eight study points.

### 3.3 Measured data inside the port

*In situ* wave measurements inside the Port of Sines were performed on both the 26th February 2009 and the 25th February 2011. At the first measurement campaign, two pressure sensors were used at two different locations (P1 and P2, Figure 3a), while at the second campaign only one pressure sensor was used (P1, Figure 3b). These measurements inside the port were used to compare and validate the significant wave heights HS predicted by the FAM network and by the DREAMS model.

Figure 3. Location of pressure sensors for *in situ* measurements: a) "P1" and "P2" on the 26th February 2009; and b) "P1" on the 25th February 2011.

### 3.4 Training of the FAM network for outside and inside the port

The Fuzzy ARTMAP algorithm was developed in MatLab® with a graphical interface based in Microsoft Excel®. The used CPU was an Intel® Core i7 2.2Ghz – 8 GB RAM.

Firstly, the offshore wave buoy values (HS, TP and DIR) were used as input to the FAM network, whereas the target output consisted of the corresponding values of HS, TP and DIR determined outside the port, at the SWAN point (Figure 2), by using the SWAN model.

In order to minimize the differences between the FAM and the SWAN results (here after called the errors) at the SWAN point, a sensitivity analysis was performed on the network parameters: $\beta$ (training rate), $\alpha$ (category choice parameter), $\rho_a$, $\rho_{ab}$ and $\rho_b$ (monitoring parameters) and $\epsilon$ (increment for $\rho_a$). The parameters that minimized the errors were: $\beta$=1.0, $\alpha$=0.1, $\rho_a$(initial)=0.9, $\rho_{ab}$=0.95, $\rho_b$=0.995 and $\epsilon$=0.001. With the above parameters, the FAM network was trained with wave buoy data from 27/01/2005 to 31/12/2010 (excluding periods without wave buoy measurements), corresponding to 14200 values. The total time for the training process was 56335 s (approximately 15h40min).

Secondly, whilst the offshore wave buoy values (HS, TP and DIR) were still used as input to the FAM network, the target output consisted of the corresponding values of HS, TP and DIR determined inside the port, at points A to G (Figure 3), by using the DREAMS model. With the same network parameters, the FAM network was trained with wave buoy data from 27/01/2005 to 31/12/2008 (excluding periods without wave buoy measurements), corresponding to 9170 values. The total time for the training process varied from point to point, with a minimum value of 1170 s (approximately 20 min) and a maximum value of 2429 s (approximately 41 min).

## 4. Results

### 4.1 Outline

In this section, a selection of the FAM results are firstly presented for the SWAN point outside the port (sub-section 4.2) and secondly for the points at the port entrance (point A) and inside the port (points B to G) (sub-section 4.3). All these FAM results are compared with numerical results from the SWAN and the DREAMS models, respectively.

Values of various statistical errors are determined, considering as reference values for the FAM predictions, *FAM(n)*, the numerical results, *Num(n)* (SWAN or DREAMS results):

$$MAPE = \frac{1}{N}\sum_{n=1}^{N}\frac{100\left|Num(n) - FAM(n)\right|}{Num(n)} \tag{1}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(Num(n) - FAM(n)\right)^{2}} \tag{2}$$

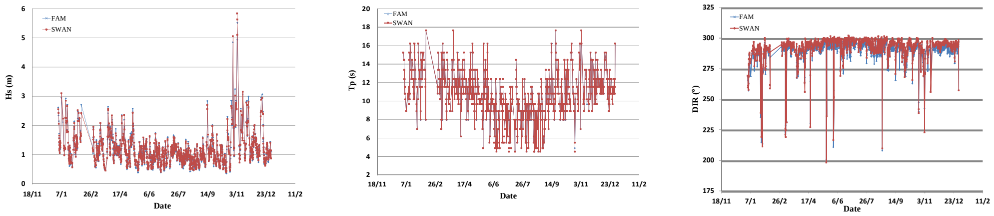
$$BIAS = NUM(n) - FAM(n) \tag{3}$$

where *MAPE* is the mean absolute percentage error, *RMSE* is the root mean square error and *BIAS* is the simple difference, for which the mean, μ, and the standard deviation, σ, are calculated.

Lastly, the FAM results are compared with the *in situ* measurements performed inside the port (sub-section 4.4).

## 4.2 FAM predictions outside the port

Predictions with the FAM network were carried out for the full year of 2011. Figure 4 presents a comparison between the FAM predictions and the SWAN results at the SWAN point, in terms of HS, TP and DIR. Table 2 presents the corresponding values of the statistical errors.



a) b) c)

Figure 4. Comparison between the FAM predictions and the SWAN results at the SWAN point for 2011: a) HS; b) TP; c) DIR.

Table 2. Statistical errors for HS, TP and DIR at the SWAN point for the year 2011.

| **PARAMETERS** | *MAPE* (%) | *RMSE* | *BIAS* | |
|---|---|---|---|---|
| | | | μ | σ |
| HS | 3.72 | 0.048 m | 0.011 m | 0.050 m |
| TP | 0.02 | 0.01 s | 0.00 s | 0.02 s |
| DIR | 0.96 | 0.2 ° | 2.6 ° | 2.3 ° |

The results show that:

- in general, the FAM predictions follow the SWAN trends of the significant wave heights, peak wave periods and directions at the SWAN point, showing a good fit to the numerical model;
- the FAM predictions for HS and DIR slightly underestimate the SWAN results, as confirmed by the positive mean values of the *BIAS* error;
- the FAM predictions for TP are very close to the SWAN results, as suggested by the nil mean value of the *BIAS* error;
- the greater *MAPE* error was obtained for HS, with 3.7%, followed by DIR with less than 1%.

### 4.3 FAM predictions inside the port

Figure 5 presents a comparison between the FAM predictions and the DREAMS model results for the year 2009, in terms of HS and DIR, at points B and G inside the port, which are the points used for comparison with *in situ* measurements in sub-section 4.4. TP predictions are not shown graphically since they fit extremely well the numerical model results, as can be observed in the values of the statistical errors presented in Table 3. This table shows the errors for all points analysed with the DREAMS model (points A to G), for HS, TP and DIR.

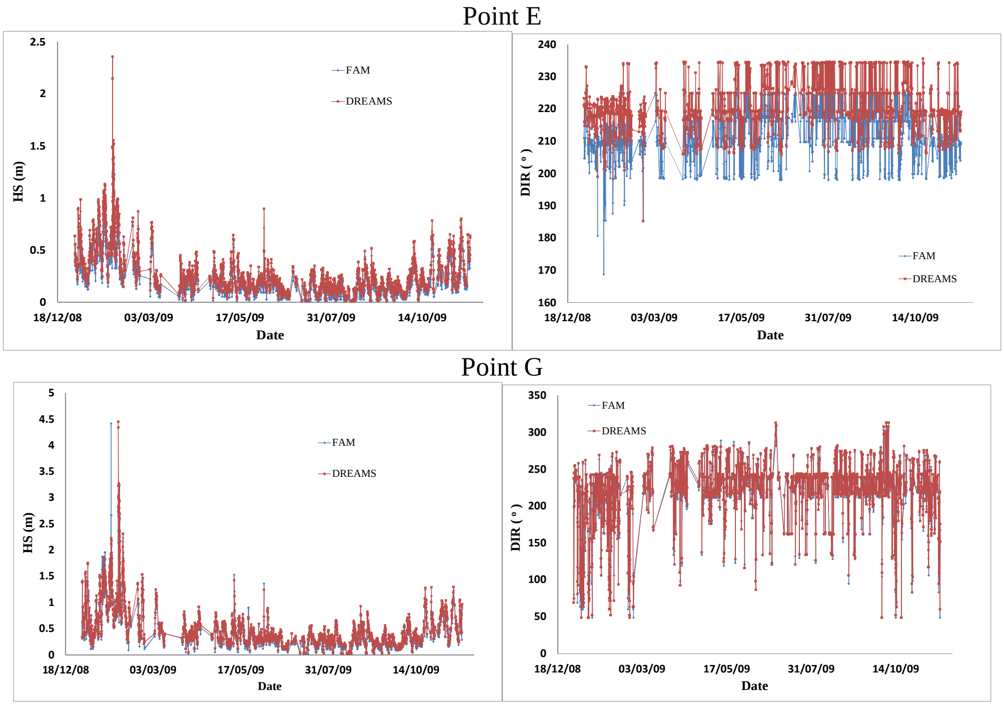


Figure 5. Comparison between the FAM predictions and the DREAMS results at points E and G for 2009, in terms of HS and DIR.

Table 3. Statistical errors for HS, TP and DIR at points A to G inside the port for the year 2009.

| **POINTS** | **HS** | | | | **DIR** | | | | **TP** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *MAPE (%)* | *RMSE* | *BIAS* | | *MAPE (%)* | *RMSE* | *BIAS* | | *MAPE (%)* | *RMSE* | *BIAS* | |
| | | | μ | σ | | | μ | σ | | | μ | σ |
| **A** | 19.013 | 0.234 | 0.287 | 0.182 | 0.849 | 0.209 | 1.757 | 3.002 | 0.046 | 0.023 | -0.005 | 0.080 |
| **B** | 15.518 | 0.077 | 0.016 | 0.059 | 8.780 | 1.038 | 11.886 | 2.972 | 0.043 | 0.022 | -0.005 | 0.078 |
| **C** | 39.878 | 0.183 | 0.087 | 0.075 | 1.197 | 0.380 | 2.994 | 6.824 | 0.048 | 0.022 | -0.004 | 0.080 |
| **D** | 29.103 | 0.183 | 0.111 | 0.137 | 2.748 | 0.438 | 5.844 | 2.654 | 0.034 | 0.019 | -0.004 | 0.070 |
| **E** | 27.233 | 0.143 | 0.068 | 0.079 | 4.180 | 0.629 | 9.221 | 1.549 | 0.027 | 0.015 | -0.002 | 0.050 |
| **F** | 21.760 | 0.053 | 0.010 | 0.024 | 7.826 | 0.823 | 7.963 | 2.488 | 0.047 | 0.022 | -0.005 | 0.076 |
| **G** | 14.176 | 0.128 | 0.048 | 0.142 | 2.191 | 0.658 | 1.750 | 7.638 | 0.049 | 0.023 | -0.004 | 0.080 |

In general, the predictions inside the port present a greater difference to the DREAMS results than the predictions outside the port did when compared to the SWAN results. This may be due to the fact that the sensitivity analysis on the network parameters was performed only for the case in which the FAM output was the wave characteristics outside the port (at the SWAN point), which means that the network predictions inside the port may not be optimized yet.

Nevertheless, the FAM predictions follow the DREAMS trends of the significant wave heights, peak wave periods and directions at the points inside the port, showing a reasonable fit to the numerical model. The FAM predictions for HS and DIR tend to underestimate the DREAMS results, as confirmed by the positive mean values of the *BIAS* error. The greatest *MAPE* errors were obtained for HS, followed by DIR. The highest relative errors are associated with the more sheltered points of the port (points C, D, E and F), which may be explained by the difficulty of the FAM network to identify the complex mechanisms of refraction, diffraction and reflection of the waves inside the port.

### 4.4 Comparison and validation with in situ measurements

The above sub-sections presented FAM predictions compared with numerical modeling results. Here a comparison with *in-situ* measurements is shown to analyze the behavior of both the FAM network and the DREAMS model.

Unfortunately, the *in-situ* measurements (see section 3.3) at points P1 (approximately point G) and P2 (approximately point E) were recorded exactly when the offshore wave buoy had stopped the data collection, resulting in a gap in wave buoy data. To overcome this difficulty, wave predictions at the wave buoy location were obtained from the WAVEWATCH III model (Tolman, 1997) and were used as input both for the FAM network and the SWAN model.

Figure 6 shows the comparison of the FAM predictions both with the DREAMS results and the *in situ* measurements for points P1 (point G) and P2 (point E) in 2009 and for point P1 (point G) in 2011. The figure shows that for P1 (G) and P2 (E), the *in situ* measurements are closer to the DREAMS results, both for 2009 and 2011, than to the FAM predictions. However, the trends of the FAM and the DREAMS results are quite similar, although the DREAMS results are always higher than the FAM ones (under prediction). This may be due to the fact that, as mentioned before, FAM network shows some difficulty to identify the complex mechanisms of refraction, diffraction and reflection of the waves inside the port.

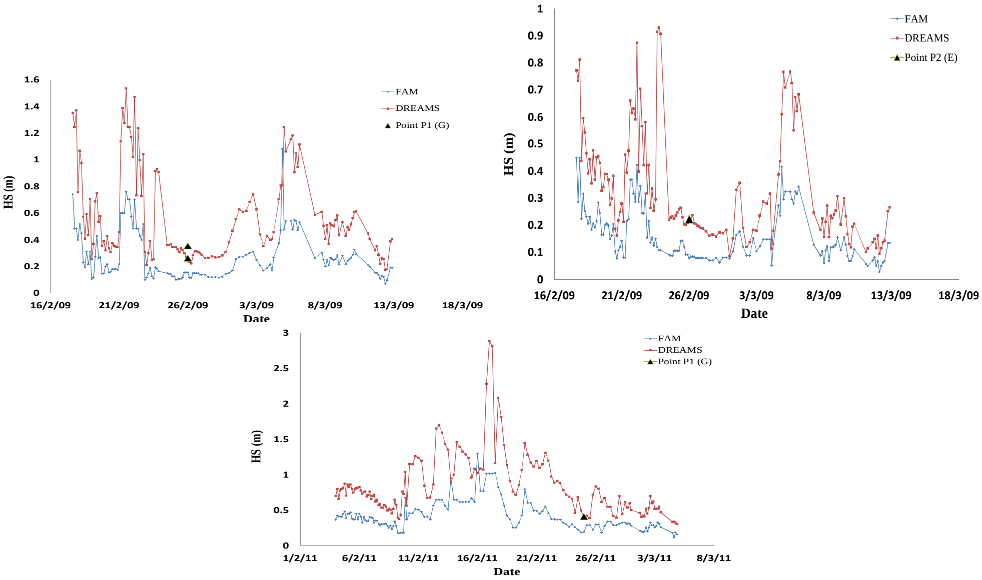


Figure 6. Comparison of the Fuzzy ARTMAP predictions with both the DREAMS results and the *in-situ* measurements for points P1 (G) and P2 (E) in 2009 and for point P1 (G) in 2011.

## 5. Conclusions

In this paper, a Fuzzy ARTMAP artificial neural network called FAM was trained to predict the wave regime at the entrance and inside the Sines Port, on the Portuguese west coast. *In situ* measurements, buoy data and results from two numerical models were used to train and validate the ANN. The wave regime was calculated for different points outside and inside the port.

Comparison between the predictions of the FAM network and the numerical model results showed that, in general, the FAM predictions followed the numerical trends of the significant wave heights (HS), peak wave periods (TP) and directions (DIR), showing a satisfactory fit to the numerical models. The FAM predictions for HS and DIR tended to underestimate the model results, whereas the predictions for TP were very close to the numerical results. The greatest differences were obtained for HS.

The predictions inside the port presented a greater difference to the numerical results than the predictions outside the port. This may be due to the fact that the sensitivity analysis on the network parameters was performed only for the case in which the FAM output was the wave characteristics outside the port, which means that the network predictions inside the port may not be optimized yet. On the other hand, the highest relative errors were associated with the more sheltered points of the port, which may be explained by the difficulty of the FAM network to represent the complex nonlinear phenomena of refraction, diffraction and reflection of the waves inside the port.

The FAM results present less promising results than the numerical model when considering the comparison and validation with the *in situ* measurements.

This fact demonstrates that the neural network still needs to be improved for protected locations inside the port by performing a sensitivity analysis on the network parameters for the case in which the FAM output is the wave characteristics inside the port.

Until this optimization is carried out and the FAM results are analysed, it is uncertain whether the FAM is a viable methodology for wave penetration inside the port.

The training time for the FAM network with over 9000 data points was very low (between 20 and 40 min) and the computational time for each prediction was even lower (less than 2 s). Consequently, this methodology proved to be able to provide a fast and satisfactory response, especially useful in the scope of forecast and warning systems.

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