An Intelligent Transportation System for Tsunamis Combining CEP, CPN and Fuzzy Logic *

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Abstract. Tsunamis and earthquakes have a great impact in human lives, infrastructures and economy. Although preventing tsunamis from occurring is impossible, minimizing their negative effects is in our hands. The aim of the Intelligent Transportation System (ITS) proposed in this paper is to provide safer routes for emergency and rescue vehicles. This system must consider the information regarding the tsunami alert system and the road state combined with the vehicle performance. Complex Event Processing (CEP) technology allows us to gather and process the information provided by authorities to establish the alert level. A Fuzzy Inference System (FIS) can be used to consider the uncertain regarding the road-status related concepts, such as, flood, objects and alert levels, and to assist authorities to determine whether roads are accessible. The information obtained through these technologies can then be used in a Colored Petri Net (CPN) model in order to obtain safer routes. This proposal has been applied to the Spanish city of Cádiz, due to its population density and its location in a small peninsula close to an active tectonic rift.

Keywords: Intelligent Transportation System · Tsunami · Complex Event Processing · Fuzzy Logic · Colored Petri Nets

1 Introduction

Sadly, earthquakes and its consequences such as tsunamies and aftershocks have a deadly impact in our societies. Recently, on early and mid February 2023, a

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series of earthquakes and aftershocks with magnitudes reaching 7.5 and 7.8 (Mw) stroke in Kahramanmaras, Turkey, and its surroundings. It had a high toll on deaths in the southeast of Turkey and the neighbour cities of Syria [19]. Other similar episode occurred on 2004 affecting the Indian Ocean and known by the scientific community as the Sumatra–Andaman earthquake [13]. It provoked a massive tsunami with waves up to 30m high, which destroyed cities and villages in the surrounding coasts of the Indian Ocean. It was one of the deadliest natural disasters in recorded history affecting 14 countries with more than 225k deaths.

This episode and the 2011 tsunami in Japan showed the necessity to establish advanced earthquake detection systems to inform both population and authorities and specially in subdue zones like the Gulf of Cadiz [16,21]. Results obtained by these works can be used for emergency and decision planners to implement tsunami mitigation measures resulting in tsunami-resilient communities.

These measures include the recommendation of reaching higher ground areas, such as high buildings in cities. Population should concentrate in specific areas and Intelligent Transportation Systems (ITSs) can therefore be implemented to determine routes for emergency and rescue vehicles. In this paper, we propose an ITS for Tsunamis to obtain safe routes considering typical tsunamis conditions, such as flood levels, objects in the pavement and new alerts. The main contributions of this work are the following:

- The design of an ITS in case of tsunamis combining Complex Event Processing (CEP), Fuzzy Inference System (FIS) and Colored Petri Net (CPNs).
- The definition of CEP patterns to determine the tsunami alert level.
- A FIS to deal with the uncertainty.
- A CPN dynamic road model considering the current conditions.
- Obtaining safe routes from the CPN model via simulation techniques.

Figure 1 shows the general diagram, depicting the different steps[3]:

(1a) Several systems provide information on the state of the city roads, and the tsunami alert system information is processed and correlated by a CEP engine, which is responsible for creating the complex events to feed the FIS.
(1b) Cádiz map is modeled as a CPN.
(2) The FIS system provides a set of recommendations stating which city areas are accessible.
(3) The domain expert states whether roads are open, pass-with-precaution or close, on the basis of the FIS recommendations.
(4) The CPN model establishes the mobility restrictions with the information obtained in step (3).
(5) An emergency officer asks for a route, taking the vehicle performance into account.
(6) The CPN model provides this user with a route, which is obtained by simulation.

An ITS is a system which could operate automatically, but some scenarios as the one considered in this work may include situations not considered during the ITS design. Therefore, the domain expert supervision is mandatory.

[3] This figure has been designed using images from Flaticon.com.

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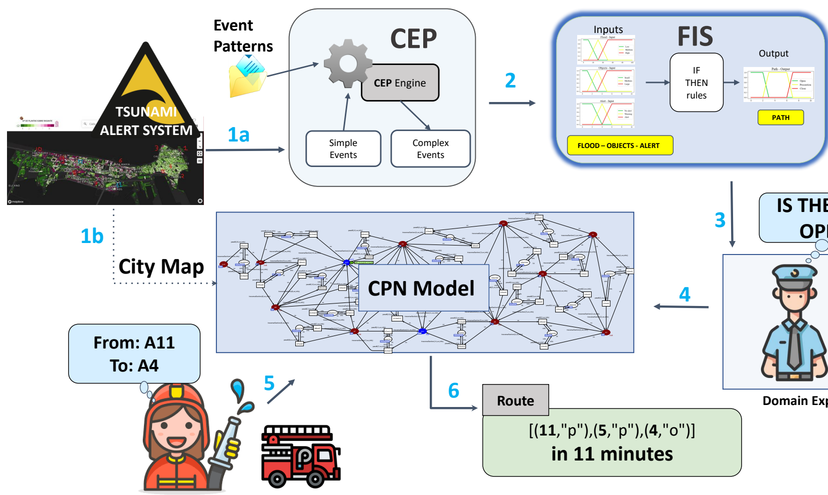

Fig. 1. General diagram of the ITS.

The structure of this work is as follows. Section 2 presents the related work and the scenario of interest is presented in Section 3. The CEP patterns are defined in Section 4, the proposed FIS inference system is introduced in Section 5, and the CPN model and the computation of safe routes are presented in Section 6. Finally, the conclusions and lines of future work are presented in Section 7.

2 Related Work

Since the post-tsunami situation usually cannot be accurately described, and information is often incomplete, decision makers do not have enough information to perform decision analysis. Therefore, uncertainty is one of the most challenging and important issues in the tsunami management. To deal quantitatively with such an imprecision or uncertainty, the fuzzy theory is adapted to disaster management studies. It is worth highlighting the work presented by Sheu in [24], in which hybrid fuzzy cluster optimization is proposed for the operation of emergency logistics codistribution responding to urgent relief demands in the crucial rescue period. In this line of research, Tsai et al. [26] apply the fuzzy set theory to decision making in a geographic information system for the allocation of disaster shelters. Öztaysi et al. present a very original proposal [22]. They present a fuzzy inference system for the management of spontaneous volunteering developed using MATLAB Fuzzy Logic Toolbox™. It is also worth commenting on the work by Carathedathu et al. [7], in which real-time feedback from sensors is sent to a fuzzy controller that predicts whether a tsunami will strike. To make the prediction it only takes into account two parameters, namely earthquake intensity and wave height. A work closer to our proposal is the study presented by Afandi and Mayasari [3], in which the authors propose an evacuation route using Dijkstra's Algorithm, where the weights of the graph are the

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fuzzy output obtained based on the length and width of the roads. From our point of view, this work would be useful in a pre-tsunami scenario to know the fastest roads. However, in a post-tsunami scenario any event may have occurred, leaving the roads in difficult conditions due to the presence of obstacles, even being closed or flooded, which are parameters that are taken into account in our model. Moreover, we would like to remark the work by Raj and Sasipraba [10], in which a fuzzy inference rule approach is used to determine which service (namely hospital, fire service or police) is the most appropriate according to the user's needs (in a post-tsunami scenario) and proposes the shortest route to reach that service using Euler's algorithm. Note that we use a different approach, as we compute the route from a fixed location (service) to a certain area, taking the road status into account, so as to avoid flooded areas and considering the times to cross the zones due to the possible obstacles in them.

Some works proposed the use of CEP technology for developing disaster and tsunami management systems [27,28]. However, these systems do not take the advantage of combining CEP with CPN and fuzzy logic. Moreover, event patterns are not defined for automatically detecting tsunami levels, as we do in our work, but for detecting sensor problems such as control error, battery alarm and loss of volts [28].

Regarding the use of Petri nets (PNs) in emergency situations, Tadano et al. [25] proposed the use of stochastic time PNs for disaster victim evacuation, considering road repair sequencing, and Yan et al. [29] used PNs as a methodology for modeling and evaluating the resilience of nuclear power plants.

We can conclude that due to the extreme need for effective disaster management, several works have been developed focusing on different topics related to disaster management, and in particular to the specific case of post-tsunami situations. Mainly, all of them make use of FISs in one way or another. However, we have not found any works that make use of CEP technology combined with fuzzy logic and CPN in an all-in-one solution. Indeed, the major contribution of the proposal presented in this work is the development of a complete system capable of providing an ITS in emergency situations composed of CEP, fuzzy logic and Petri nets which, to the best of our knowledge, has not been yet proposed.

3 Application Scenario

In some previous works [9,5,14], we used CPN models of some Spanish cities for different purposes, such as to obtain routes to reduce pollution, or to avoid close areas in the case of a pandemic, etc. In this paper, we consider a city map for Cádiz city (located in the south of Spain, at latitude 36.52672 and longitude -6.2891). Cádiz is the eighth city more densely populated in Europe due to its location in a small peninsula and it is located close to an active tectonic rift. The city already suffered the devastation of the earthquake occurred in 1755, known as the Lisbon earthquake and future episodes are expected in the area of the Straight between Iberia and north Africa [8]. The hazard planning envisioned for this city includes the recommendation of taking shelter in high grounds. Cádiz peninsula is flat, and thus, we have considered its highest building areas shown in

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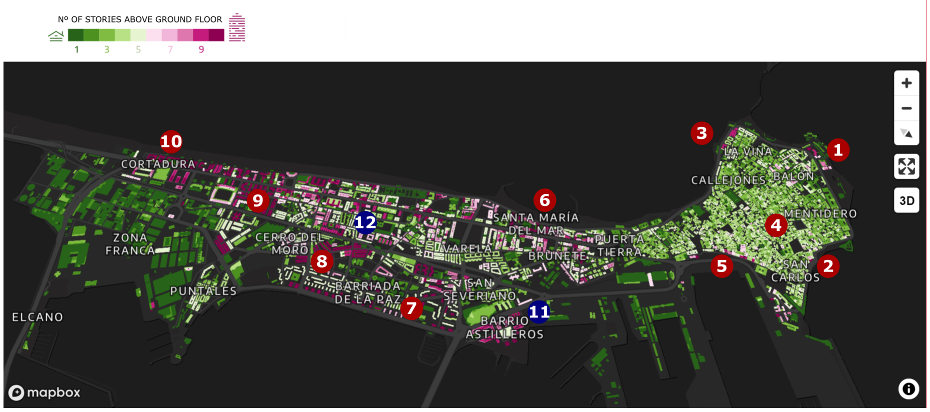

Fig. 2. Map of the Cádiz city.

Figure 2. This model consists of 12 areas, taking into account the high buildings in each area, with at least seven stories high[4].

The scenario we consider is the following. After a tsunami, people have sheltered in these buildings. Emergency services, such as paramedical and firefighters, are requested to attend citizens at these areas. A route has to be provided to reach these areas, but objects in the road washed away by the tsunami, flood levels and new incoming alarms can determine whether the mobility is restricted. Emergency services departs from areas 11 and 12, where the firefighting headquarter and the ambulance base are located, respectively. Thus, the routes are obtained from either zone 11 or 12 to any other zone in the city.

We based this scenario on Cádiz, since this is a well studied location for tsunamis and action plans have been provided by authorities [6], but this work can easily be adapted to other locations and the criteria to establish the zones could also be modified in order to consider other parameters of interest.

4 The CEP event patterns

CEP is a cutting-edge technology for analyzing and correlating huge amounts of real-time data with the aim of automatically detecting situations of interest (event patterns). These event patterns must be previously implemented using an Event Processing Language (EPL) and then deployed in a CEP engine, the software responsible for data analysis and event pattern detection.

To automatically detect the three tsunami levels according to the Spanish state plan for civil protection against tsunamis [6], we defined three event patterns (*Info*, *Warning* and *Alert*) by using MEdit4CEP [4]. This is a graphical modeling tool that facilitates domain experts to model event patterns that are transformed automatically into Esper EPL code [2], which is then deployed in the Esper CEP engine.

As an example, Figure 3(a) depicts the *Warning* event pattern modeled with MEdit4CEP, while Figure 3(b) shows the Esper EPL code automatically gen-

[4] Designed using the mapbox by Raúl Sánchez, elDiario.es (CC BY-NC 4.0).

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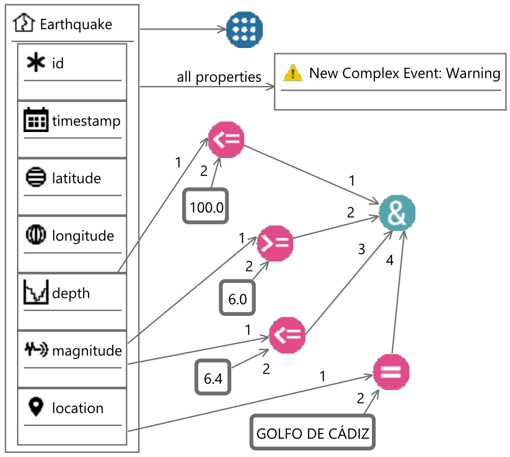
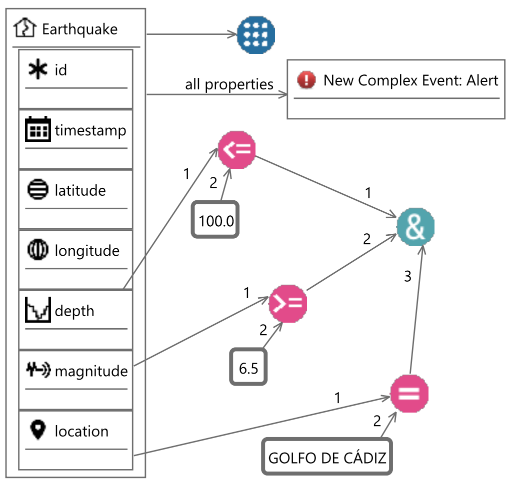


(a) Model

```
@Name("Warning")
insert into Warning
select a1.*
from pattern [(every a1 = Earthquake(
  (a1.depth <= 100.0 and
  a1.magnitude >= 6.0 and
  a1.magnitude <= 6.4 and
  a1.location = 'GOLFO DE CÁDIZ')))]
```

(b) Esper EPL code

Fig. 3. *Warning* event pattern.



(a) Model

```
@Name("Alert")
insert into Alert
select a1.*
from pattern [(every a1 = Earthquake(
  (a1.depth <= 100.0 and
  a1.magnitude >= 6.5 and
  a1.location = 'GOLFO DE CÁDIZ')))]
```

(b) Esper EPL code

Fig. 4. *Alert* event pattern.

erated from the designed model. Mainly, this pattern looks for every occurred *Earthquake* event whose depth is less than 100 km., the magnitude is between 6.0 and 6.4, and the location is equal to "GOLFO DE CÁDIZ". When these conditions are satisfied, a *Warning* complex event is created by the CEP engine, which is notified to our proposed FIS. Similarly, Figure 4(a) illustrates the *Alert* pattern designed with MEdit4CEP, while Figure 4(b) shows the Esper EPL code automatically generated. This pattern looks for every *Earthquake* event whose depth is less than 100 km., the magnitude is greater than or equal to 6.5, and the location is equal to "GOLFO DE CÁDIZ". If so, an *Alert* complex event is created and notified to the FIS.

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5 The Fuzzy Inference System

FIS is a suitable decision-making system that can be used in the case of natural disasters [22], considering that the inputs and outputs of these systems cannot be sharply defined. We use the Mamdani type FIS [15], considering a set of linguistic rules obtained from domain experts, where the antecedents and the consequents of the rules are expressed as linguistic variables using fuzzy sets [30]. This FIS system provides a highly intuitive knowledge base, being easy to understand and maintain. It is implemented via the Skfuzzy Python toolbox [20], where the `trampmf` and `trimf` membership functions are used to specify the fuzzy sets. We use the default parameters established in the Skfuzzy toolbox, which are: minimum as t-norm (AND operator); t maximum as t-conorm (OR operator); minimum (Implication operator); maximum of consequent fuzzy sets as aggregation method for combining rule consequents; and the defuzzification method used is the centroid (center of gravity).

The fuzzy sets of the input/output variables considered for this FIS are shown in Figure 5. This FIS only considers three input variables: *flood*, *objects* and *alert*, and a single output variable (*path*). The values of these variables are normalized in a range from 0 to 10, except flood, which is expressed in centimetres, from 0 to 100. In all cases, high values correspond to high values in the registered measurement.

The alert input variable is obtained from the CEP engine taking into account the magnitude property obtained from the detected events. In the case of flood and objects, a low value corresponds to a good condition and a high value means unfavourable conditions for emergency vehicles. We assume that these inputs are provided by authorities using Machine Learning (ML) technologies, a well known technique used in this domain [18]. Then, they are classified in the linguistic labels: Low, Medium and High for flood; Small, Medium and Large for objects; and Info, Warning and Alert for alerts.

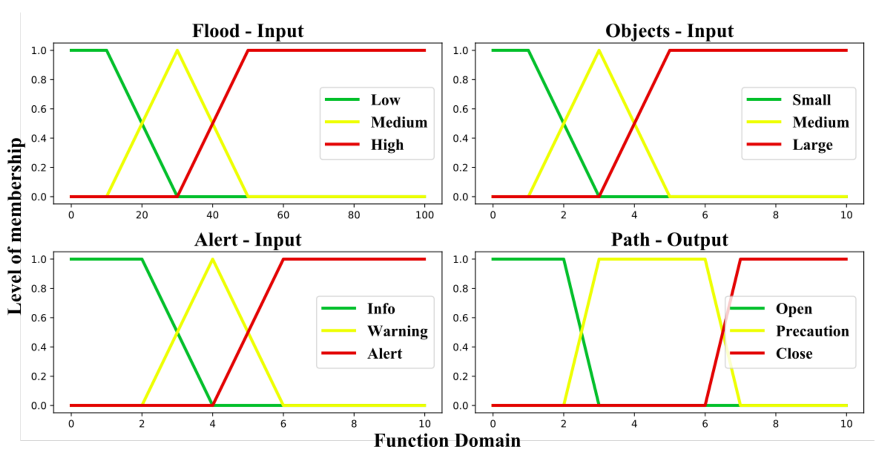

Fig. 5. Input/Output membership functions.

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The output variable *path* is also defined in the range 0-10 and the linguistic label classification is the following: *open* (pass without restrictions), *precaution* (can pass with caution, only allowed for vehicles with special performances) and *close* (access is not possible). Table 1 contains the IF-THEN rules defined.

Table 1. IF-THEN Rules for FIS.

1. IF *flood* is `Low` AND *objects* is `Small` AND *alert* is `No alert` THEN *path* is `Open`
2. IF *flood* is `High` OR *objects* is `Large` OR *alert* is `Alert` THEN *path* is `Close`
3. IF NOT (*flood* is `Low` AND *objects* is `Small` AND *alert* is `No alert`) AND NOT (*flood* is `High` OR *objects* is `Large` OR *alert* is `Alert`) THEN *path* is `Precaution`

Figure 6 illustrates the three surfaces obtained considering these rules and the alert levels 2 (Info), 4 (Warning) and 9 (Alert), respectively. For instance, the output is *Precaution* (4.01) taking as input 25 for flood, 2 for objects and 2 for alert, and, for an alert of 9, considering the same input values for flood and objects, the output is *Close* (8.23).

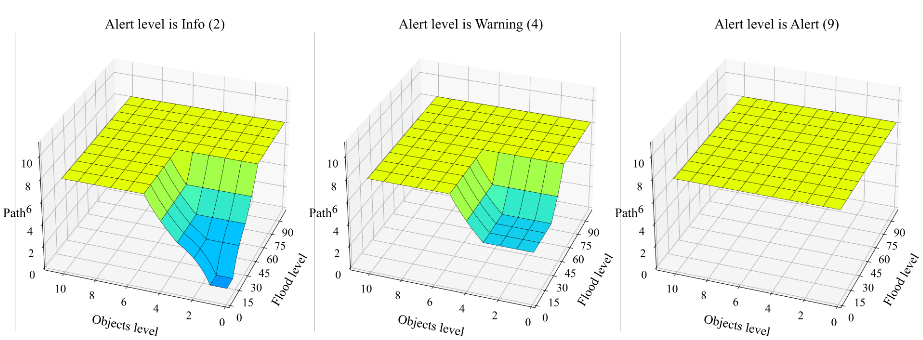

Fig. 6. Fuzzy space.

6 CPN model

PNs [23] are a well-known graphical formalism that allows us to model concurrent systems and analyze their behavior. PNs are bipartite directed graphs with two types of node: places (drawn as circles) and transitions (drawn as rectangles). The system states are usually represented by the markings of the places (number of tokens on them), while the events producing changes in the system state are modeled as transitions. The arcs can only connect places with transitions and

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vice versa, and they have a weight associated, which indicates the number of tokens to be removed from the corresponding precondition place or the number of tokens to be added to the corresponding postcondition place of the transition that is executed (*fired* in PN terminology). CPNs [11] extend the plain model with both data and time information in the tokens. CPN Tools [1] is the tool used in this work for editing, simulating, and analyzing CPNs, and therefore, we use the notation of this tool [12]. In CPNs, each place has an associated color set (*colset*), which is similar to a data type, and the tokens on the place must then belong to the colset of the place. Color sets are indicated below the places, in their right bottom part. Transitions can have priorities and guards to restrict their firing. The latter are Boolean expressions constructed using variables, constants and functions, and they are indicated above the transitions, on their left hand-side. Arcs have an expression associated, which must evaluate to a multiset of the color set of the attached place. The *enabling condition* and the *firing rule* are extended to consider the time and data information. Due to the lack of space we omit the technical details, which can be found in [11]. Informally, when a transition is fired under a certain *binding*[5], we remove from its precondition places a number of tokens equal to the resulting value of the expression of the arc connecting the place with the transition, and for the postcondition places we add a number of tokens equal to the resulting value of the corresponding arc expression.

Figure 7 shows a piece of the city map, in which we can see the two color sets that we use: `ZoB` and `I4`.

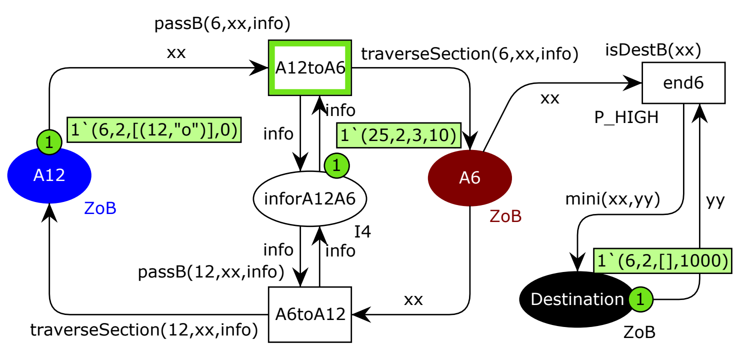

Fig. 7. Detail of the city map.

These color sets are defined as follows:

```
colset INTR=product INT*STRING; | colset ZoB=product INT*INT*INTlistR*INT;
colset INTlistR=list INTR;      | colset I4=product INT*INT*INT*INT;
```

[5] Bindings are variable assignments, considering the tokens on the precondition places, and the variables labeling the arcs.

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ZoB values consist of 4 fields. The first two elements are integers indicating the destination and the vehicle type, respectively. In this paper, two types of vehicle are considered: vehicles of type 1, which can only pass under favorable road conditions (Open); and vehicles of type 2, which can also pass under certain unfavorable road conditions (Precaution). The third field represents a route with a list of traversed zones and its mobility conditions (”o” or ”p”, open and precaution, respectively). The last field indicates the total time to follow the route. As an illustration, let us consider the token in the place *A12*: `1‘(6,2,[(12,"o")],0)`. This token indicates a route to zone 6 for a vehicle of type 2, which starts at zone 12, mobility is permitted and the total time is 0.

The color set *I4* consists of four integer elements, which represent the flood, objects and alert levels, and the last field contains the average time required in normal conditions to cross this zone. As an illustration, the marking of the place *inforA12A6* states that the flood is 25 cm, the object level is 2 and the alert level is 3, with a travel time of 10 minutes between zones A12 and A6.

The funtions used in the guards are the following:

```
fun noReturnB(i:INT,yy:ZoB)=not( mem (#3yy) (i,"o")) andalso
                            not( mem (#3yy) (i,"p"))
fun isDestB(xx:ZoB)=  hd(rev (#3 xx)) = (#1 xx,"o") orelse
                        hd(rev (#3 xx)) = (#1 xx,"p")
fun isOpenB(i:INT,yy:ZoB)=noReturnB(i,yy) andalso not(isDestB(yy));
fun OpenType(xx:ZoB,info:I4) =
  if (simFIS(info) <3) then true
  else if((simFIS(info)<7) andalso (#2 xx) > 1) then true else false;
passB(i:INT,yy:ZoB,info:I4)=isOpenB(i,yy) andalso  OpenType(yy,info);
```

Function *noReturnB* avoids coming back, i.e. we cannot cross twice the same zone. Function *isDestB* is used to check if we have reached the final destination. These functions are used to define *isOpenB*, which determines whether a route is open or not. Function *passB* uses the expert assessment based on the FIS information to determine if we can traverse a zone depending on the vehicle performance (function *OpentType*).

The functions used in the arc inscriptions are the following:

```
fun tComp(info:I4) = (((#1 info) div 10) + #2 info + #3 info) * 2 div 3;
fun tB(info:I4)= (#4 info) * tComp(info);
fun fis(info:I4)= if  simFIS(info)<=3  then  "o"  else   "p";
fun traverseSection(i:INT,xx:ZoB,info:I4)=
            (#1 xx, #2 xx, (#3 xx)^^[(i,fis(info) )], #4 xx + tB(info));
fun mini(y:ZoB,z:ZoB)= if (#4y < #4z) then 1‘y else 1‘z
```

Function *tB* is used to compute the times to cross from one zone to another, where the average time to cross between them is proportionally incremented by the level established by the domain expert (*tComp*). The information stored in the *ZoB* places is updated using the traverse function *traverseSection*. It adds to the route the new traversed zone, indicating whether the crossing is open or the

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vehicle must proceed with precaution. This is made using the expert assessment (*fis*). It also updates the total travel time.

With the marking indicated in Figure 7, the guard *passB* is satisfied, and thus the transition *A12toA6* is enabled and can be fired. The token in A12 is removed with its firing, and a new token is produced in place A6, with values `(6,2,[(12,"o"),(6,"p")],40)`. Thus, the emergency vehicle is now in zone 6, it must proceed with precaution, and the total time elapsed in the route is 40 minutes. Function *tComp* was evaluated to 4 following the expert decision.

Place *Destination* represents the final destination. This place is reached via the transition *end6*, which is fired when it is enabled due to its high priority. It is enabled when the guard *isDestB* indicates that we have reached our destination. Function *mini* is used to replace the previous value of the token on this place with the new information (best route to the previous one). In our case, the new value for this token would be `(6,2,[(12,"o"),(6,"p")],40)`.

Finally, we performed 100 simulations and we obtained the best route from these simulations depending on the information offered by the CEP system, the FIS and the expert decisions. The whole CPN for the map of Cádiz is depicted in Figure 8. The case under analysis is an ambulance of type 2 traveling from zone A12 to A6. The information to cross between both areas now is `(50,6,2,10)` with a FIS output closed (8.23) and therefore the expert has decided that this crossing is closed. An alternative is crossing from A12 to A11, and then to A6. In this case, the information is `(30,3,2,10)` and `(3,2,2,2)`, and the route `(6,2,[(12,"o"),(11,"p"),(6,"o")],54)` with a total travel time of 54 minutes. There are other faster alternatives to this route, for instance, the ambulance can proceed via A12 to A8, A7 and A6 with a total travel time of 26 minutes `(6,2,[(12,"o"),(8,"o"),(7,"o"),(6,"o")],26)`. In this case, the information considered for each crossing is `(13,0,2,8)` `(4,1,2,5)` and `(7,1,2,7)`, respectively. The faster time is obtained because the expert has judged that the conditions for crossing these areas are better.

7 Conclusions and Future Work

The ITS proposed in this paper provides a system to obtain safe routes for emergency and rescue vehicles. It complies the three main properties that an ITS must hold, i.e., it must be able to consider the traffic flow, it must be adaptable to capture the system dynamics, and must be concise but able to represent new application scenarios.

The traffic flows represented as routes in maps are modeled via CPNs and tsunami alarms are gathered from the authority systems. These alarms are processed by the CEP technology to feed a FIS with which authorities can assess the road state. These assessments can be used by the CPN to establish the available routes. Simulation allows us to repeat the experiment and thus obtain a short route, as the best of the ones obtained by the simulations. The CPN model has the main advantage that it immediately takes into account the current road and alert conditions, as they are indicated in the markings, and no structural change

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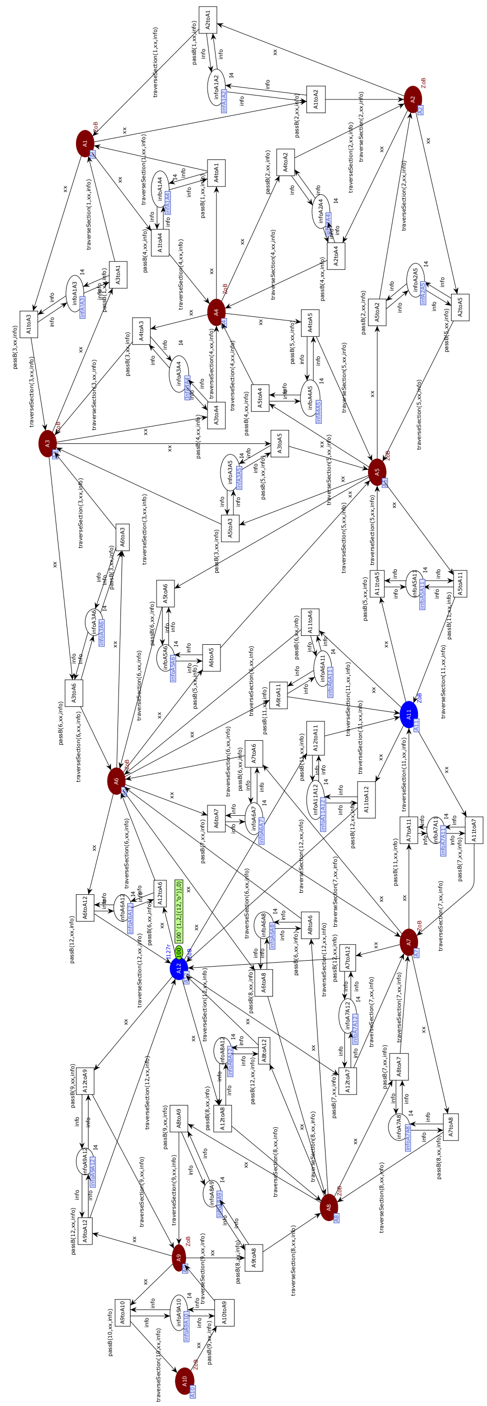

Fig. 8. CPN page of Cádiz Map.

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is required in the model. Thus, this ITS is flexible and the routes are obtained according to the current scenarios.

As future work, we intend to apply Machine Learning and Deep Learning techniques [17] to gather the road situations regarding flood and objects. External communication with the CPN model can be implemented in CPN Tools to achieve this goal. In addition, we plan to perform a usability study through a comparison with existing works in this area.

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