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Knowledge-based models for emergency management systems

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Abstract

This paper proposes the use of advanced knowledge models to support environmental emergency management as an adequate response to the current needs and technology. A generic architecture embodying the knowledge pieces required to manage emergencies in different kinds of problem scenarios is described. Simulation models of the physical system, integrated as part of the knowledge architecture, are also claimed to be adequate, both from the point of view of the knowledge model calibration and the training of the emergency personnel as well. The feasibility of the approach has been demonstrated with the application of the generic model to a particular real world problem: the management of flood emergencies in the Jucar river basin area (Spain). This work was developed in the framework of ARTEMIS, a European Commission research project. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Knowledge architectures; Emergency management; Decision support systems

1. Introduction

The management of emergencies, resulting from natural or man-made disasters, requires enough information as well as experienced responders both in technical and co-ordination matters. Information requirements may be partially satisfied with the development of telematics systems, which make it feasible to build up applications integrating sensors, communications and real-time data bases to provide raw information about the state of a natural or artificial installation such as a chemical plant or a watershed. In this way, a great amount of information is available that should be used to improve the management of the emergency, which generally means making the best decision at the right moment. In order to support the decision-makers in the evaluation of this raw information, knowledge-based systems (KBS) are good candidates, as they are able to integrate both theoretical and common sense knowledge directly taken from the expert decision-makers. Furthermore, KBS are able to provide explanations of their recommendations; this is of fundamental importance in any emergency domain, as the responsible personnel cannot adopt a decision without fully understand it.

In this context, the European Commission research project ARTEMIS[1] shows an approach for the development of knowledge-based emergency management systems. In addition to the expertise model of the responsible personnel, simulation models of the physical system being monitored also are discussed. Two sample mock-ups of the final systems were developed in order to show the feasibility of the proposal: one of them in the flood emergency domain and another one for the management of emergencies caused by industrial accidents (e.g. heavy gas dispersion).

The content of this paper starts with the identification of general human–computer interaction requirements for Emergency Management Systems. In particular, a domain-independent set of questions relevant in the management process followed by the responsible people will be defined. Next, both the simulation and the generic knowledge models are described. Then, the Knowledge Structure Manager (KSM) tool is proposed to operationalise the described knowledge model structure. Lastly, the mock-up for the flood emergency domain is summarised.

2. User–system interaction in emergency management scenarios

An intelligent system capable of assisting human operators in the management of emergency situations should be capable of providing justified conclusions on:

- the more relevant observable events with their diagnosis, i.e. the current situation of the installation or area being monitored;

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- the short-term evolution of the situation within different possible scenarios;
- the advisable decisions to be taken in order to avoid the problems or minimise their consequences.

In this context, according to the importance of an adequate user–system interaction, the design of this type of systems may start from the specification of a *conversation model* (Hernández & Serrano, 2000). This model may contain the collection of classes of questions and answers that may be exchanged between the user and the system, structured according to the needs of an emergency responsible in a generic episode (domain independent). The top level of this structure may include three main classes of queries:

- *What is happening?* The answer to this type of question may be the description of the current situation in part or the whole area under control. It could be generated from a specific demand of the user or from a warning-oriented performance of the system. Derived questions may be 'what may happen' or 'what to do', but also there may be others asking for a description of the state of the environment, the state of the control devices/resources or explanations.
- *What may happen?* In this case a description of foreseeable situations that may be possibly reached under different hypothesis would be obtained. The hypothesis or parameters associated to these queries may concern the area where the evolution wants to be studied, the environmental conditions to be considered (e.g. the best possible, the real ones or user defined) and the control actions (e.g. the active ones or user defined). Derived questions may ask for explanations or for a corresponding 'what to do' query.
- *What to do?* After any of the previous queries, the answer to this one provides a proposal of control actions to be taken to overcome a problematic situation. The parameters accompanying this query may refer to the part of the system where a solution is required, hypothesis/constraints on the availability of the control resources (e.g. none, predefined or user defined) and hypothesis on the active control actions.

3. Requirements for an intelligent emergency management system

Building an intelligent system capable of supporting the previous generic conversation model requires the development of two kinds of models:

- simulation models that emulate the behaviour of the real-world environment for the supervised area or installation;
- knowledge models that embody the conceptual aspects and the corresponding reasoning methods required to perform the monitoring and management of emergency situations.

The first type of model is very important to test and validate the knowledge model. Obviously, emergency management systems are used only when an emergency happens, or may possibly happen. In the real world, this does not happen very often. However, the human organisation and the supporting systems must be in an adequate condition to give the required answers in all possible emergency situations.

To make this possible, the approach is to design artificial generic models of reality, flexible enough to deal with the typical information environment for emergency management. These models may allow the users to input information about varied events, representative of the possible emergency situations. Operating the knowledge model with data provided by the artificial reality model may also be useful for the training of human teams responsible for decision-making.

Section 3.1 includes the description of a generic artificial model of reality. Section 4 presents a generic knowledge model for emergency management.

3.1. The artificial model of reality

The environment of the area or installation being monitored can be represented by a time series of values for the variables that characterise its on-going situation. These variables can be: (i) numerical, representing measures obtained through sensors and communications; and (ii) qualitative, representing measures estimated by personal appreciation.

Accordingly, the artificial model of reality should be capable of generating such time series taking into account the fact that:

- at any instant, t, the generated variables, are consistent, i.e. the simultaneous values of variables satisfy the physical relations, representing a temporal cross-section of the global phenomenon which is being represented;
- the relations among values on consecutive time steps satisfy the physical conditions for representing the evolution of the phenomenon.

Then, the model may consist of:

- a set of constraints representing the conditions for consistency between simultaneous data;
- sets of constraints modelling cause–effect on-going relations between subsets of variables (every subset may characterise an aspect of the physical behaviour). These sets of constraint must be partially ordered since the initial causes may generate effects that are causes of other effects and so on. Several chains of this type may be feasible according to the partial order structure.

These cause–effects models should include models of behaviour of the physical phenomenon and its response to control actions and civil protection actions. The general cause–effect structure, i.e. the process of generating series

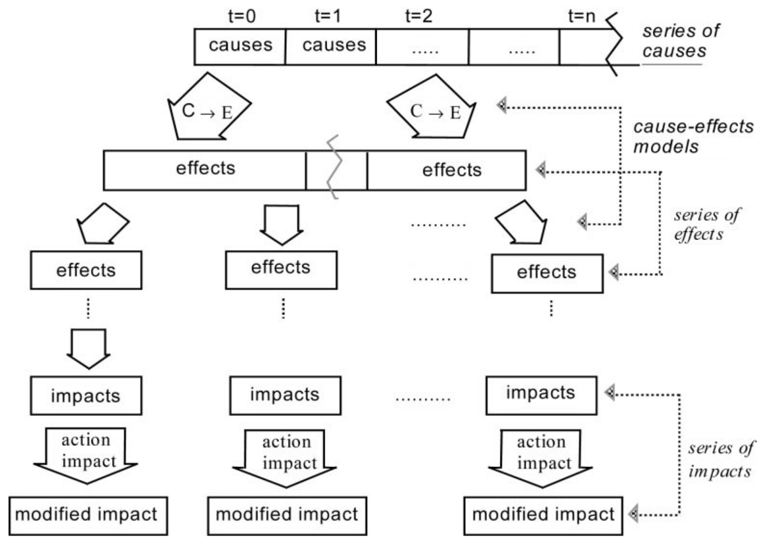

Fig. 1. Cause–effect propagation structure in an artificial reality model.

of effects starting from a series of causes is summarised in Fig. 1. The diagram shows the way of computing effects at different levels. The arrows represent the different models relating causes to effects and intermediate effects to other effects. The process ends with the expected impacts that may be modified by the application of a model of action–impact, represented in the low-level arrows.

The application of this model in the context of flood management may require the following types of variables:

- rainfall variables representing the rainfall state at every pluviometer integrating the data network;
- flow variables representing flows in the network of river channels in the upper basin;
- control device state variables representing the situation of gates, spills, etc;
- water level variables representing levels in lower river reaches where overflow may be produced or water level variables in the flood plain where evolution of a flood may be represented;
- impact variables representing effects on towns or roads.

The first three types of variables may be numerical and the last two may be qualitative.

The corresponding artificial reality model may be defined by:

- A collection of constraints among rainfall values expressing the coherence in rainfall situations (i.e. it is not possible that rainfall in area A be more than double that in neighbouringarea B, if it is raining in A there will also rain in C, etc.).
- A causal model *rainfall(t)* $\rightarrow$ *flows(t* $+ \Delta t$*)* expressing the effect of the rainfall in the watershed reception areas on the upper level river channel network. The constraints may represent the relation between a unit of rainfall during a predefined time period and the flows drained for an area, which is usually named unit hydrograph.
- A causal model *flows(t)* $\rightarrow$ *flows(t* $+ \Delta t$*)* representing the relations between upstream flows in different links and downstream flows in the river channel network. This type of model is known in hydrology as the Muskingum type, which formulates the characteristics of the output hydrograph in a river link from the input hydrograph, the initial state of the link and the physical characteristics of the link channel represented by some parameters. The proposed constraint system may qualitatively represent this relationship between hydrographs for every link, i.e. the flow routing in the river channel network.
- A causal model *flows* $\rightarrow$ *water levels*. This type of constraint expresses: (1) the measure relation between flow and water level in a section at the same time t; and (2) the impact of upstream flows in the water levels that the downstream lower river reaches Δt instants later. The latter models the effect in water level changes along the lower river reaches produced by the incoming flows from upstream basins.
- A model *water levels* $\rightarrow$ *water levels* expressing the propagation of changes of flood wave along time in lower river reaches.
- A model *water level(t)* $\rightarrow$ *impacts(t* $+ \Delta t$*)* representing the relation between water levels in the river channels in some instants and impacts on infrastructure points Δt instants later. This is a classification model relating effects on the areas neighbour to the river and water level situations (e.g. if water level in A is $\geqq T$ in the next 1 or 2 h, the main street of the town B may be flooded around 40 cm).

When the final impacts have been inferred, new components of the model may be established to simulate the effect of control actions and civil protection actions on these impacts. For the different possible actions, cause–effect models of the following type may be defined for every type of impact:

$$\text{situation}(t)\text{actions}(t, t+\Delta t) \rightarrow \text{situation}(t, t+\Delta t)$$

Once a model structure is formulated by a collection of constraints of the previous types, it may be used to generate an event by propagating the effects of a given time series of primary causes along the chains of cause–effect relations represented in the model. With the application of every cause–effect submodel, several possible effect values satisfying the constraint conditions may be obtained. As the model is being used to generate a plausible event, a single random solution is generated, satisfying the conditions which will be used as input for the next cause–effect application step.

For instance, in the case of floods, the primary causes is the rainfall time series in the different areas of the basin. This time series is propagated through the different constraint models, representing relationships between upstream river channels and reception areas. This may produce flows along the network that may be translated to water levels in some significant points, and again the water levels may be translated to potential impacts in the surrounding areas. After the potential impact has been established, the human operator may react with control and civil protection action plans. These plans may be described by a collection of time series actions that may be used together with the current situation of impacts to generate a new situation of impacts.

4. A generic knowledge model for emergency management

In general, the design of a knowledge model is based on a sequence of refinement steps, starting from a general valid reasoning method capable of meeting the goals of the target application. For emergency management, a valid reasoning strategy may be: (i) identifying undesirable situations; (ii) analysing their causes and predictable effects; and (iii) identifying actions to be applied on the causes in order to avoid or alleviate the expected undesirable impacts. This sequence of reasoning may provide answers not only for the *what to do* classes of questions but also to the *what is happening* and *what may happen* questions.

Then, three main classes of knowledge may be required as shown in Fig. 2.

4.1. Incident identification knowledge

This may be defined as a collection of hierarchically organised predefined classes of incidents, expressed using a frame-based representation formalism. Once an observed incident is included in a certain top level class in the hierarchy, additional detail features are inferred, which are used to identify subclasses of the incident and so on until the maximum level of specificity available is reached. The output of this reasoning may include several potentially

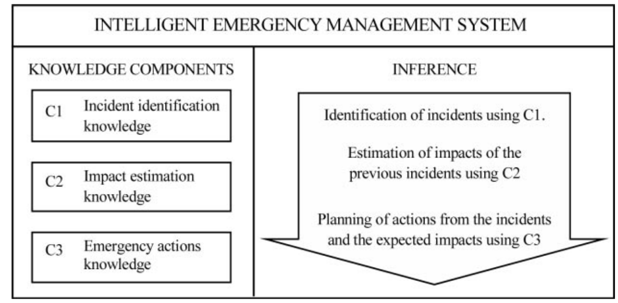

Fig. 2. General reasoning method for emergency management.

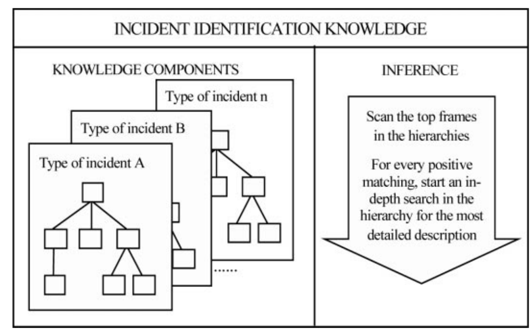

Fig. 3. Incident identification knowledge unit.

happening situations according to a high matching level with some of the predefined incidents (Fig. 3).

4.2. Impact estimation knowledge

This describes a situation in the evolution of the hazardous phenomenon. Two levels of information may be considered:

- State of parameters characterising the physical evolution of the phenomenon. This is the case of the state of flows in the river channels and water levels in some of these river channels along time.
- State of parameters characterising the situation of some relevant elements of the natural environment, social environment, communications and transport network. This is the case when the water levels may affect a river, a reservoir or a railway network.

The inference of the impacts may be performed by the following reasoning method:

1. Start from the known current situation described by the values of the state parameters.
2. Estimate scenarios of short-term evolution of external actions on the phenomenon. This is the case of rainfall in floods as natural external actions and different human-based control decisions as artificial ones, such as gate control actions in reservoirs.
3. Apply a model of the physical behaviour of the phenomenon in such a way that a short-term evolution estimate of the state parameter values is obtained. Several

models may be used: (i) a calibrated numerical model that proposes, after the integration of the physical phenomenon equations, the most accurate prediction. This approach requires very accurate available data for the initial state and the external actions. If this is not the case, as these models require fully specified numerical inputs, it is necessary to generate a collection of possible numerical combinations representing the ambiguous information (usually value intervals for the evolution of the initial situation and external actions evolution are known). In this case, the inference process would be very inefficient because the number of combinations required to representatively evaluate the collection of environment combinations multiplies the complexity of the process of numerical integration. (ii) A qualitative model that using a constraint-based version of the equations governing the physical behaviour of the phenomenon obtains its possible short-term states. This approach is more practical because in the case of ambiguous information previously commented, this type of information can be managed by the qualitative models using quantity spaces described by a discrete set of intervals. (iii) A simplified version of the previous approaches could be defined by providing, for every type of phenomenon, a *compiled* version of the simulation step in terms of a transition graph between physical states labelled with the parameters of the environmental conditions. This type of model may consist of a collection of transition frames formulated for different short-term periods (i.e. there may be a knowledge base of 1 h transition, 2 h transitions …) in the cases where the number of parameters ensure a reasonable size of the knowledge base.

Anyway, a mixed approach to these models may be used if an *if needed* procedure is associated to the slots of estimated parameters. The *if needed* procedure may be a qualitative or quantitative simulation model. This type of frame may be read as a statement such as: *if the initial situation is of class A and the external evolution is of type B then an evolution in terms of C may be expected.* But also it may be used to support questions of the type: *to have a level C in parameters P1, P2 in the next n hours an evolution of type B in the external parameters E1, E2 should happen (including human decisions).* So the knowledge contents of the frame are valid for prediction assessment and for control decision estimation.

4. Evaluate the impacts once the evolution of the state parameters is known. To meet this final objective a knowledge-base organised by mapping relations between states of the phenomenon and impact level on significant elements may be applied. As the impact receiver areas are predefined, a rule base evaluating the impact level in every relevant element derivable from the predictable situations may be used. This is an important aspect because given the simplicity of the prediction applied, it may happen that different future situations scenarios are predicted. In order to assess the potential impact at a particular point, the possible influence derived from every scenario must be included. This is required because if all the predicted phenomenon situations generate state parameters from which it is possible to deduce influence in an element, this element may run more risk than another element that is only influenced by one of the possible scenarios.

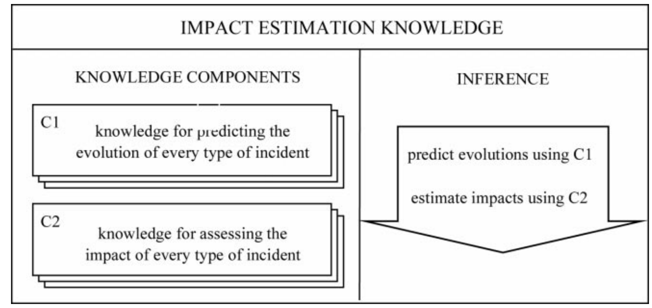

Fig. 4. Impact estimation knowledge unit.

In summary, two types of knowledge can be distinguished in the impact estimation knowledge: (i) knowledge for predicting the evolution of every kind of incident; and (ii) knowledge for evaluating impacts (Fig. 4).

4.3. Emergency actions knowledge

This is used to generate proposals of decisions to be taken in the following aspects: assignment of responsibilities, civil protection, technical control, and road network management. Defining different knowledge units for each of these activities, the inference procedure may consist of sequential calls to each of them.

- The *responsibility assignment* knowledge unit may be a primary knowledge unit formulated as a rule base with two levels of reasoning: first, the organisation and service affected are deduced and then, the responsible person in every organisation and service is defined.
- The *civil protection action* knowledge unit may be organised in three parts: the fire brigade, the evacuation knowledge and the sanitary knowledge. The inference procedure may decide, according to the characteristics of the situation, the part that needs to be involved in the emergency action (e.g. it may happen that a given situation does not require the fire brigade but only evacuation or sanitary actions). Each of these civil protection knowledge components may usually be formulated using rules, although a *case based reasoning* approach may also be applied. In this case, a collection of predefined emergency plans would be available and the reasoning method may first select the more similar cases and next adapt them to the peculiarities of the current case. This method would be supported by knowledge about similarity and plan repair. This approach may be seen as a knowledge-based version of the conventional

technique supported by humans who use a database of emergency profiles. The *technical control* knowledge unit may be based on a *generate and test* strategy:
  - first, taking into account the potential impacts, a collection of possible action plans capable of alleviating the damage are generated;
  - next, the previous proposal are evaluated using a simulator to finally select the more valuable ones.
- The *network management* knowledge unit may include two main knowledge components:
  - The collection of origin–destination couples (O–D) in the network, together with the corresponding itineraries, connecting them in a convenient order; and
  - The topology of the transport network represented with the O–D couples and intermediate nodes and considering the links as roads.

The reasoning process using these components may:

- Identify the links affected by the impact of the hazardous phenomenon. This method may not only be based on the direct cuts generated by the phenomenon, but also on the induced ones by lack of accessibility between nodes.
- Identify which of the itineraries between the relevant O–D couples have been affected by the cuts in order to generate messages for drivers recommending alternative routes.

5. Operationalization of the knowledge model

The knowledge model whose components have been described in the previous section can support the operator-system conversation schema, described in Section 2. A whole picture of the abstract structure of this knowledge model is shown in Fig. 5. As can be seen in this figure, the proposed model is a complex structure that uses different knowledge representations (e.g. rules, frames, constraints) to express different types of knowledge (e.g. control knowledge and domain knowledge) at different levels of abstraction. In fact, it is a hybrid architecture including both knowledge-based modules and conventional algorithmic modules.

Starting from the model designed, two topics arise:

- On the one hand, it has to be implemented to create a computational version following certain quality requirements (e.g. efficiency, robustness, accuracy, etc.).
- On the other hand, it must be structured in order to facilitate its understandability and maintenance, presenting to the end-user natural and intuitive images of the knowledge included in the model.

In order to satisfy both requirements, a solution is to use the KSM (Knowledge Structure Manager) tool (Cuena & Molina, 1997). KSM provides two main facilities: (i) a methodology for designing and developing structured knowledge models; and (ii) a software environment that assists a developer in building, operationalising and maintaining these models.

The KSM methodology was used to design the knowledge model for emergency management described in the previous section and represented in Fig. 5. According to this methodology, a knowledge model is considered a structure of certain descriptive entities, called *knowledge areas*, organised in a hierarchy of levels of aggregation. The top-level area represents the whole model and is decomposed into simpler areas that encapsulate the expertise that support the reasoning methods. Each knowledge area follows the intuition of a body of knowledge that explains a certain problem-solving behaviour and is described with two parts: (i) its own knowledge represented by other simpler knowledge areas; and (ii) its functionality represented by a set of tasks. In turn, each task is another description entity that represents a basic function provided by a knowledge area (e.g. identify incidents or estimate impacts) and includes *problem-solving methods* to describe the strategy of reasoning to achieve the goals represented by the task.

Using KSM, a developer can formulate generic domain-independent descriptions of knowledge models, like the one shown in Section 4, which may be reused later to build particular models on certain domains through the instantiation of the generic structures with the corresponding specific domain knowledge (e.g. for floods management, described in Section 6).

In addition to this knowledge model design methodology, KSM also gives support to develop the operational version of the model with reusable software components. These components, called *primitives of representation*, provide standard knowledge representation languages and inference mechanisms (e.g. rules, frames, etc. with forward chaining, pattern matching, etc.) useful to implement the bottom knowledge areas in the knowledge model. However, given that real applications usually require implementing ad-hoc software components, this library is open to include new domain dependent components.

Thus, the generic knowledge structure developed with KSM can be seen as a useful software tool usable for building a wide range of emergency management systems. The tool facilitates the knowledge acquisition process, since it provides the knowledge modules involved in the reasoning process and the way of expressing every type of knowledge involved in the problem solving process.

Fig. 6 shows the KSM structure developed for the model described in Fig. 5. By clicking on the different boxes, the associated inference methods and knowledge bases may be accessed and modified by the operator if needed.

6. Application on the floods domain

The above sections described the requirements of an intelligent system for emergency management support, as

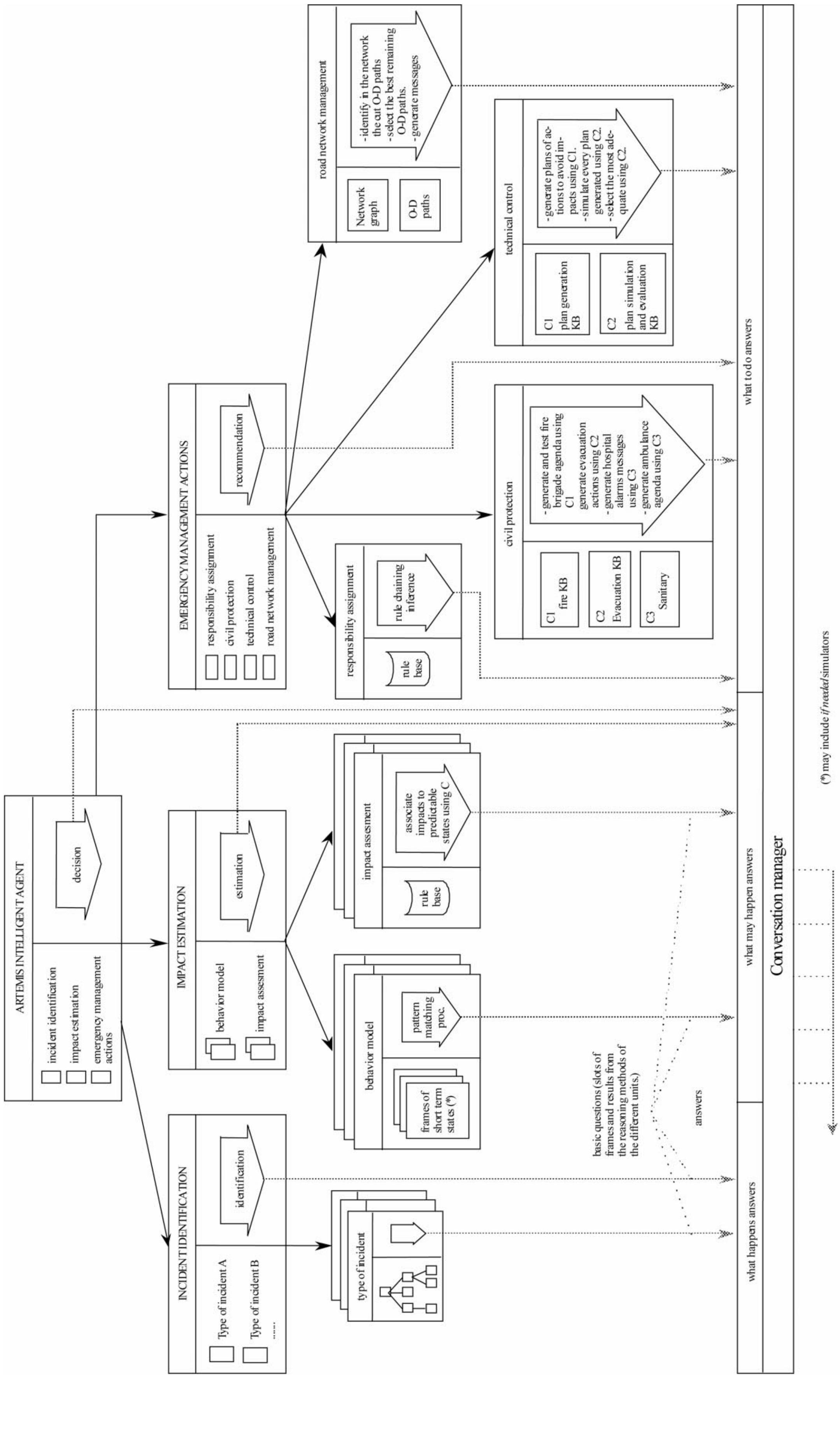

Fig. 5. Knowledge structure of the generic knowledge model for emergency management.

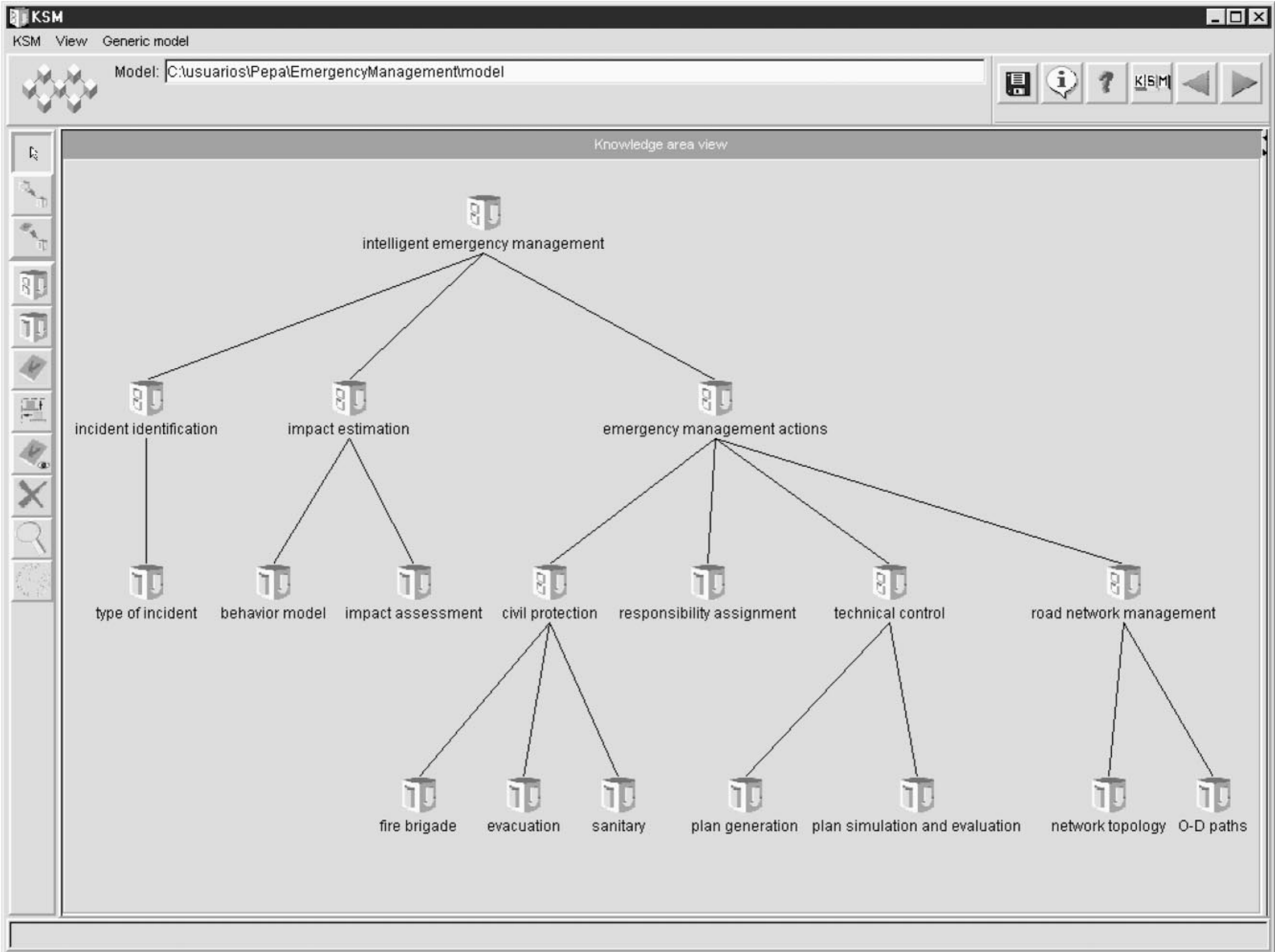

Fig. 6. Generic KSM model for emergency management.

well as the type of models necessary to make it possible. In this section, we describe the mock-up developed in the ARTEMIS project in order to demonstrate the adequacy of both the requirements and the models in a specific domain: flood emergency management. In this project, a demonstrator in the domain of industrial accidents was also developed. Both of them consist of two different parts:

1. a prototype of the final system's user interface, aiming to show the prototypical interaction that would take place in the case of an emergency scenario happen; and
2. a simplified version of the knowledge model, implemented with the KSM tool, which may support the system's answers.

Section 6.1 summarises both parts of the ARTEMIS demonstrator for flood emergencies.

6.1. User–system interaction in a flood emergency situation

In order to illustrate the kind of user–system interaction proposed, a flood emergency situation in the *Jucar* basin, caused by an excess rainfall, was considered. This region would be the whole system to be monitored by the ARTEMIS application. Briefly, the episode starts with the detection of a strong rainfall in the *Jucar* area, one of the areas in which the whole basin might be divided. These adverse environmental conditions cause the flows in the upper streams of the *Jucar* and *Sellent* rivers to grow in such a way that the water levels in the *Jucar* down river will increase accordingly. Some hours later, this will cause the river to overflow in some of its sections. These incidents in the river network will be the cause for the floods at different elements of the basin: populations of *Sueca* and *Cullera* and certain sections of the road network are the main elements affected.

Two major stages can be distinguished in the emergency scenario: the first one corresponding to a *pre-incident* phase, in which the overflow has not yet happened, and a second one in which the incidents and impacts appear. From the point of view of the decision-makers, the associated phases in the management of the emergency are those of *preparedness* and *response*. In the first one, the responsible people are interested in the monitoring of the physical system (the river network), so as in its expected evolution (forecasting of water levels, flows, level of flooding in populations, etc.). Their last goal is to obtain enough knowledge about the

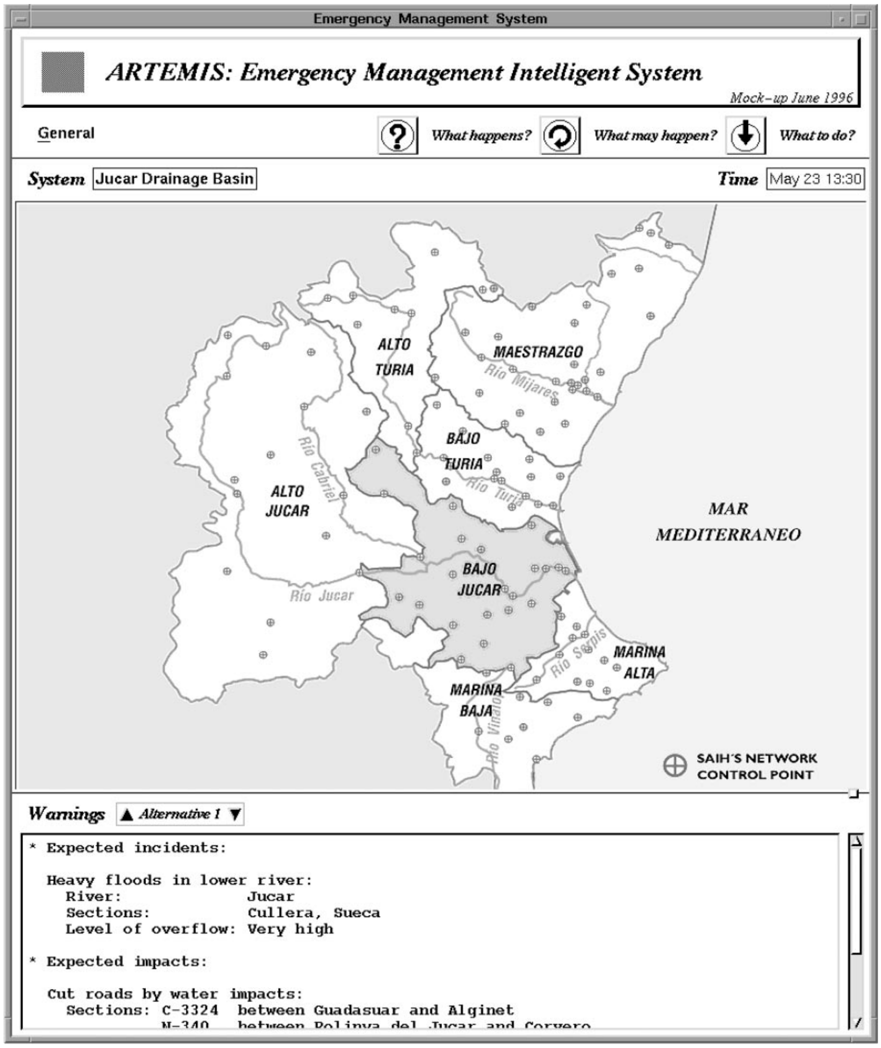

Fig. 7. Main window of the ARTEMIS flood application.

current and expected situation in order to avoid the possible river overflow. In this way, adequate control actions on the reservoirs (the major control device in this domain) will be taken. In addition, defence organisations (fire brigade, civil protection, etc.) might be asked to get prepared for action. The focus in the next phase shifts to the impact area. In this stage of the management, the elaboration of proper response plans to be executed by the different defence organisations, in order to avoid or alleviate the effects of flooding, will be given priority.

The mock-up for the flood domain included two possible interactions between a decision-maker and the ARTEMIS application: one of them corresponding to the pre-incident phase of the emergency scenario, and the other one to the incident phase. The ARTEMIS application's role can be considered as that of an expert assistant knowledgeable about the goals of the responsible personnel, as described in the last paragraph. Taking into account the more general interaction requirements (for any kind of environmental emergency) described in Section 2, the dialogues were centred on *What is happening*, *What may happen*, and *What to do* questions.

The mock-up's interface of the Flood-ARTEMIS application consists of a main window from which the user can ask for; (i) an evaluation of the current situation; (ii) the foreseeable incidents and impacts; or (iii) the set of emergency plans, by pushing the corresponding buttons. Secondary windows allow the user to specify each of the possible questions, and others let the system present its evaluations, control plans, etc.

Let us describe a first interaction sample concerning the pre-emergency stage with some detailed answers from the system: The dialogue starts with a proactive warning shown in the main window (see Fig. 7) concerning the possible incidents and impacts that could take place in the following hours, affecting the *Jucar* area. Then, the decision-maker asks ARTEMIS to elaborate on the information about the problem: a situation of high flows in the transport channel of the *Jucar* river is described, showing the state of the river

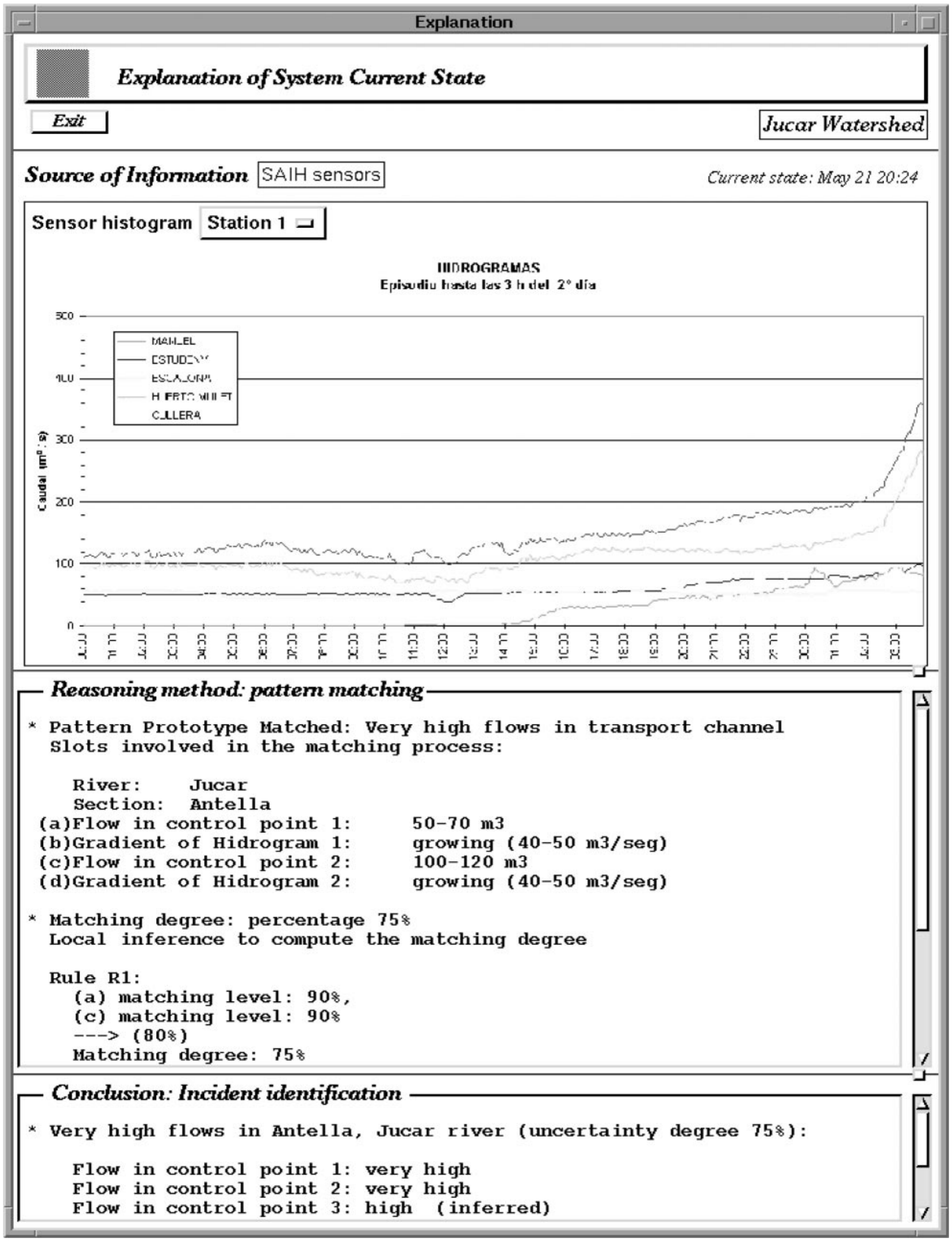

Fig. 8. Explanation of a problem detection.

network (*high flows in Antella, and Manuel sections of the Jucar river*, etc.).

Next, the operator asks for an explanation of this evaluation, i.e. he/she requires a justification of the ARTEMIS' inference that led to that conclusions. A general pattern of explanation was defined, consisting of two major parts: the premises of the reasoning task, and the knowledge used. In this case, the premises are composed of the relevant raw data obtained from the telematics network (rainfall detectors, etc.). The knowledge used consists of a frame describing the problematic situation in terms of the appropriate variable's ranges. The explanation window is shown in Fig. 8, where the raw data is presented by means of the corresponding time series.

The next question is about the possible consequences of the current problem. In this way, those responsible will get a better understanding of the problem's severity, and the resulting need to adopt control decisions. The result of the forecasting is shown in Fig. 9: flooding problems around the *Sueca* and *Cullera* sections of the *Jucar* river can be observed.

Thus, the next step of the decision-maker is oriented towards the identification of appropriate control decisions on the *Tous* and *Escalona* reservoirs that would prevent the foreseeable overflowing and flooding. In this sense, the demonstrator provides the user the alternative to specify some control action manually (see Fig. 10, where different opening degrees of the reservoir's

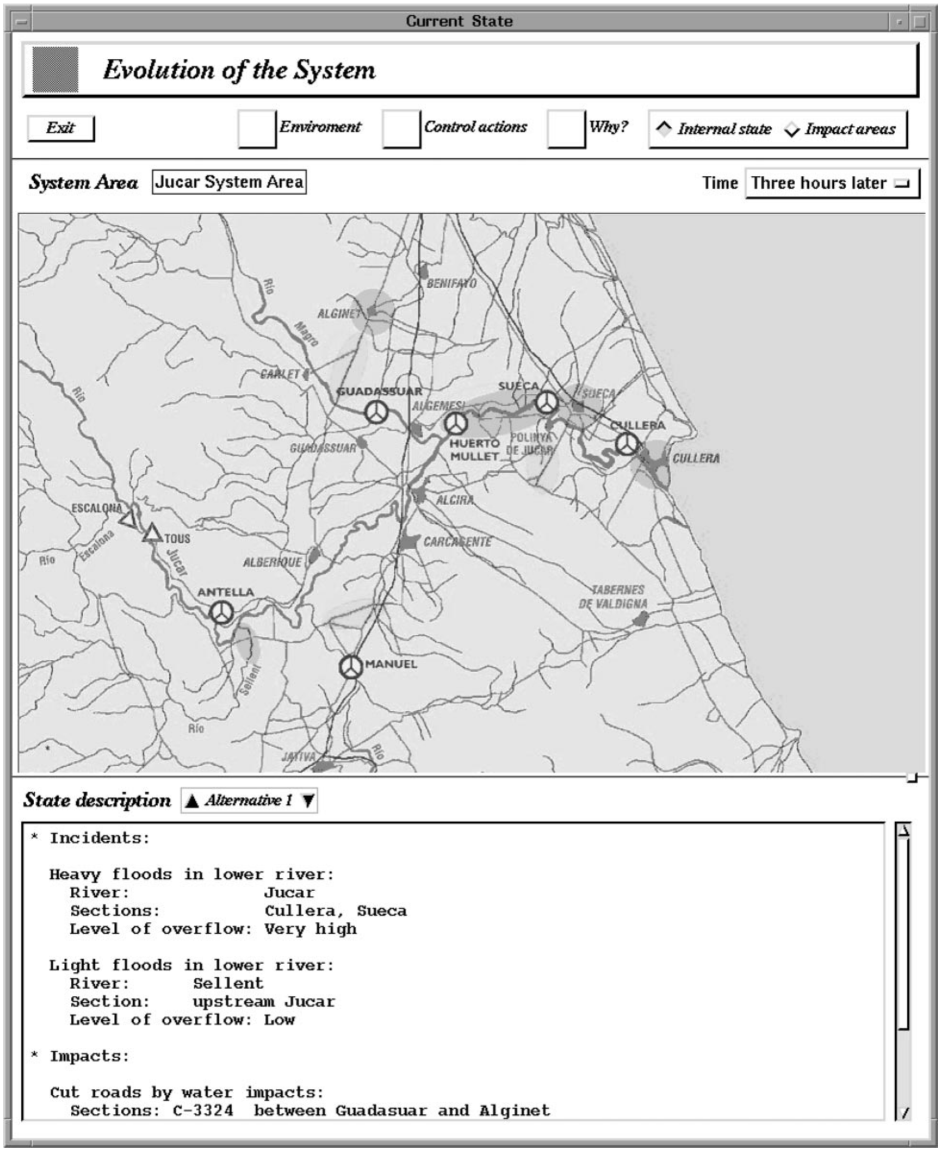

Fig. 9. Foreseeable flooding areas.

floodgates can be defined), and to test it by means of a question such as *what may happen if this control action is implemented?*

Another alternative is to ask the application directly for its suggestion. Fig. 11 shows the ARTEMIS' answer to this question. The emergency plan proposed at this moment basically consists of control actions in the reservoirs of the *Jucar* system area, and alerting the fire brigade, police traffic, etc., to the foreseeable dangers.

At this point, the dialog corresponding to the pre-emergency state finishes. The next dialog included in the mock-up corresponds to the emergency stage. It may start with an alarm issued by ARTEMIS as incidents and impacts are currently happening. Because a quick answer is required, no question about the future evolution of the situation is asked, and the operator requires the system to perform a plan proposal.

6.2. Knowledge model requirements for flood emergency support

Here, the knowledge-based architecture of a system

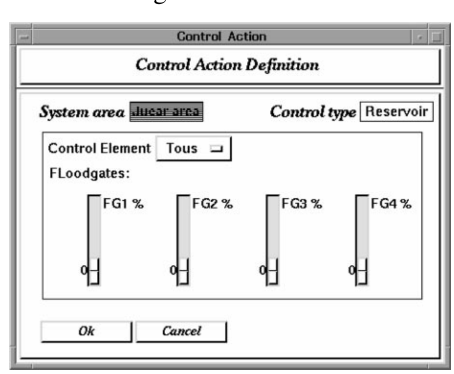

Fig. 10. Definition of control actions for the Tous reservoir.

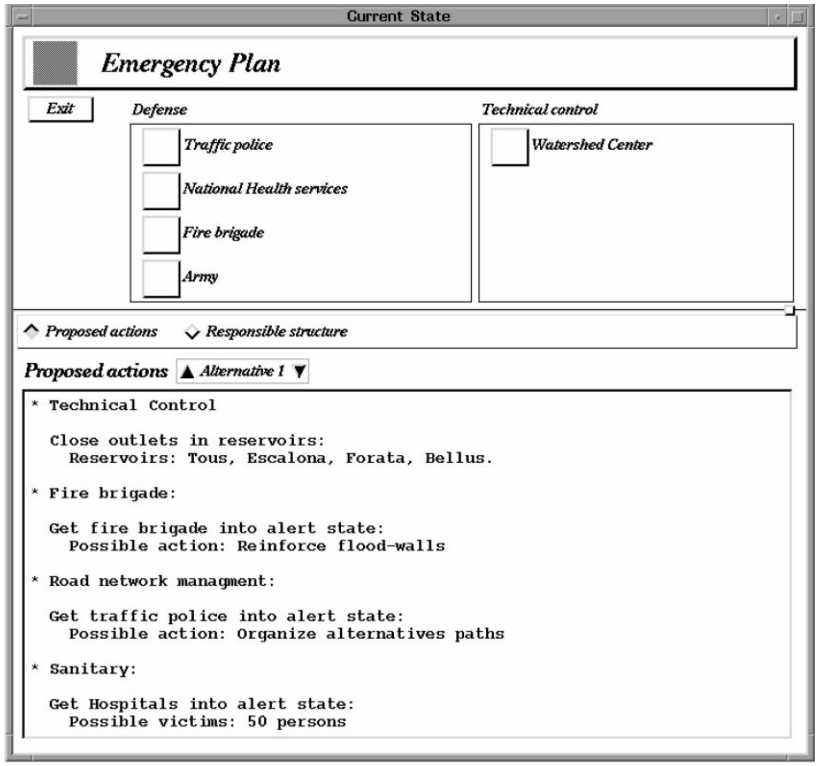

Fig. 11. Emergency plan for a possible pre-incident phase.

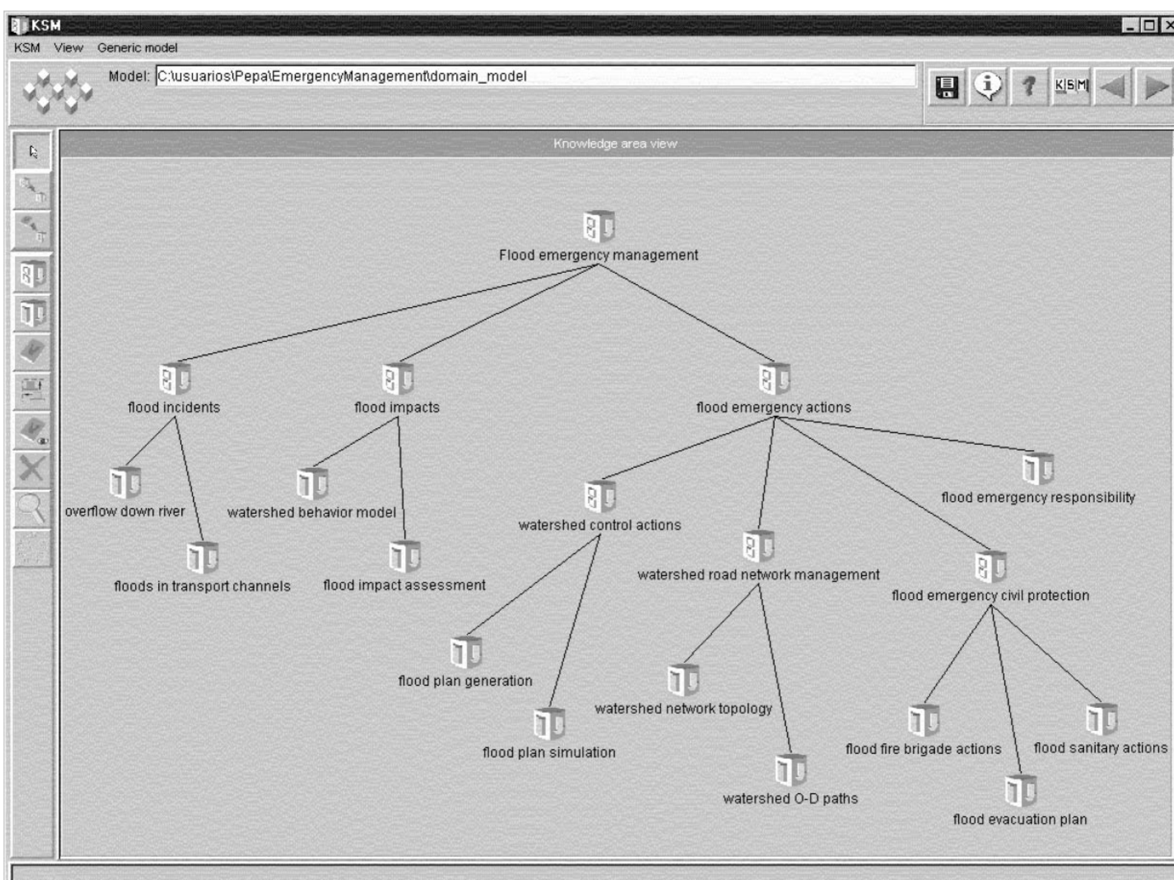

Fig. 12. Knowledge structure for the flood-emergency domain.

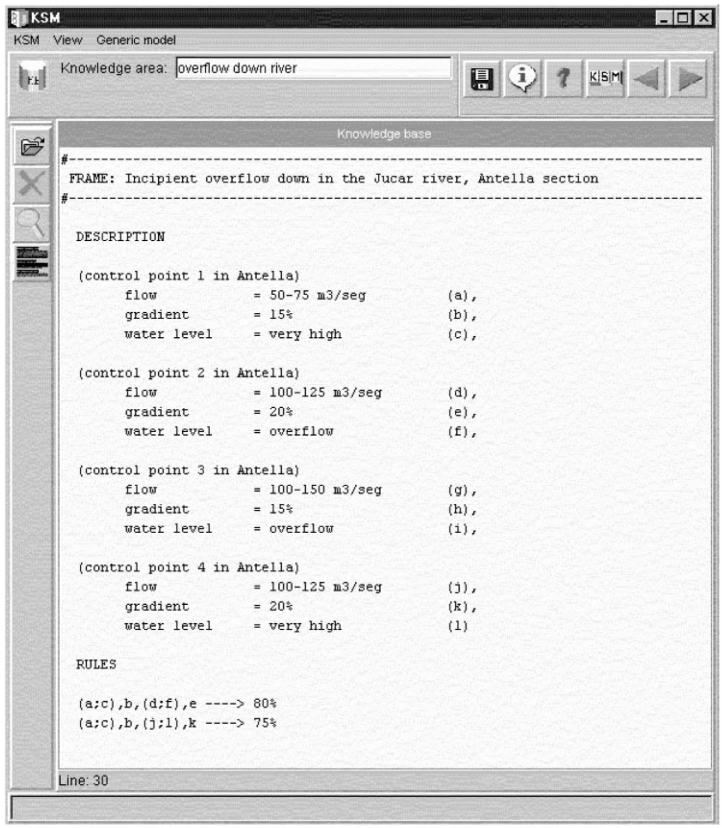

Fig. 13. Example knowledge base on overflows.

capable of providing the required answers in the previous flood emergency scenario is described. This architecture can be considered an instantiation of the generic model, described in Section 4, for any kind of emergency situation. Fig. 12 shows the domain knowledge model, specialised with the KSM tool in the floods domain.

The whole knowledge for flood emergency management is represented by the top-level knowledge area called *flood emergency* management. Following the generic model, this area is decomposed in the knowledge required for incident detection, impact estimation and emergency response:

- In the case of the flood domain, the first type of knowledge corresponds to the different kind of incidents that can be identified in the river network. Each of them would be represented by an instantiation of the generic knowledge area *type of incident*. In this type of emergencies, the overflowing in the lower parts of the river and floods in the upper transport channels are relevant incidents. A set of frames can be used to represent the knowledge in both cases. For instance, Fig. 13 shows the knowledge base for the primary knowledge unit *overflow in lower river*. The content of this base would be the different frames associated to the different situations that can be considered as overflows. The one that is shown in the figure characterises an incipient overflow in the *Antella* section of the *Jucar* river, by defining the proper ranges of the flow, its gradient, and the water level attributes.
- The possible impacts are the floods caused by river overflowing at different elements of the watershed: populations, service areas, etc. The knowledge to infer these hazards will be included in the *flood impact assessment* knowledge area, which would use information about the likely situation in the next hours. This forecast would be obtained thanks to the behavioural model of the watershed linked to the *watershed behaviour model*.

Concerning emergency action planning, the model includes a body of knowledge for each of the major organisations, identified in Section 4, that might intervene in the management of the emergency. Their specific knowledge, relevant for the management of flood emergencies, would be associated to the different primary knowledge areas. Thus, the *fire brigade actions* area may contain the knowledge used to infer the reinforcement of flood-walls are necessary in some sections of the river, given the current and expected situation. In addition, the resources for this task (pumping groups, construction machinery units) may be given as well, by taking into account the severity of the incidents. On the other hand, the watershed control centre is the organisation in charge of the control action planning. The corresponding knowledge areas will allow for the identification of the possible actions in the watershed reservoirs.

7. Conclusions

Drawing on simulation models of the physical system and expertise models of the decision-makers, the efficiency of environmental emergency management can be greatly improved. This is the major claim of the ARTEMIS project. An attempt has been made to show this by stating the interaction requirements that a management system for any environmental emergency situation should satisfy. AI approaches (Cortés et al., 2000) and in particular knowledge-based techniques have shown to be adequate to support this kind of services and interaction model. But not only this, since the model proposed is generic, a high level of reusability of the approach is guaranteed. Emergency management systems for different kinds of problems may be obtained by specifying the domain knowledge associated to the knowledge blocks included in the model. In addition, the resulting domain model is open to the operators, making possible an easy updating of its contents. The feasibility of the knowledge modelling approach for building complex decision support systems, like the one described in this paper, has also been demonstrated in other domains like traffic management with successful results (Scemama, 1994; Cuena et al., 1995; 1992).

Further steps in this direction have been given by Avouris (1995) and Cuena and Ossowski (1999) illustrating the possibilities of the distributed knowledge-based approach in the design of environmental emergency management systems.

References

Avouris, N. (1995). Cooperating knowledge-based systems for environmental decision support. *Knowledge-Based Systems*, *8* (1), 39–54.

Cortés, U., Sànchez-Marrè, M., Ceccaroni, L., R-Roda, I., & Poch, M. (2000). Artificial intelligence and environmental decision support systems. *Applied Intelligence*, *13* (1), 225–239.

Cuena, J., & Molina, M. (1997). KSM: An environment for design of structured models. In S. G. Tzafestas, *Knowledge based systems. Advanced concepts, techniques & applications.* Singapore: World Scientific Publishing Company.

Cuena, J., & Ossowski, S. (1999). Distributed models for decision support. In G. Weiss, *Multiagent systems—A modern approach to distributed artificial intelligence*. Cambridge, MA: MIT Press.

Hernández, J. Z., & Serrano, J. M. (2000). *Expert Systems with Applications*, *19*(4), 289–304.

Cuena, J., Ambrosino, G., Boero, & M. (1992). A general knowledge-based architecture for traffic control: The KITS approach. *International Conference on Applications of Artificial Intelligence in Transportation Engineering*.

Cuena, J., Hernández, J. Z., & Molina, M. (1995). Knowledge-based models for adaptive traffic management systems. *Transportation Research*, Part C, *3* (5), 311–337.

Scemama, G. (1994). CLAIRE: A context-free AI-based supervisor for traffic control. In M. Bielli, G. Ambrosino & M. Boero, *Artificial Intelligence Applications to Traffic Engineering*. Beist, The Netherlands: VSP.