Architecture of a Natural Disasters Management Framework and its Application to Risk Assessment

[1]José R. R. Viqueira, [2]Pedro Álvarez, [1]José Varela, [1]Pedro J. Saco
1 Systems Laboratory
Department of Electronics and Computer Science
Instituto de Investigacións Tecnológicas. University of Santiago de Compostela
Campus Sur, 15782 Santiago de Compostela, Spain.
{joserios, eljpet, elpedro}@usc.es
2 Advanced Information Systems Group
Department of Computer Science and Systems Engineering
Centro Politécnico Superior. University of Zaragoza
María de Luna 1, 50018 Zaragoza, Spain.
alvaper@unizar.es

SUMMARY

In this paper, the service-based architecture of a framework for the management of natural disasters is presented. This proposal combines last trends in the design of Geographic Information Systems, namely web service technologies and OGC standards (including the Sensor Web), with Multicriteria Decision Analysis techniques, which enable the incorporation of the expert's knowledge into the system. The framework becomes this way a real Spatial Decision Support System. Research needs identified during the design of the architecture are described in the paper. Finally, the forest fire risk assessment in Galicia is considered as a real scenario for the application of the proposed framework.

KEYWORDS: *Risk assessment, Web-service frameworks, MCDA, OGC standards, Sensor Web*

INTRODUCTION

Natural disasters such as forest fires, oil spills, earthquakes and floods are a source of high economic, environmental and human impact. Every year, thousands of human lives are lost, millions of people bear the destruction of their homes and an invaluable economic harm is made. It has been estimated that a new big disaster arises every three days, whereas local and regional authorities must manage the thousands of emergencies that take place every year.

Obviously, emergency management focuses on saving human lives and decreasing economic influence. Nowadays, these objectives are reachable due to the technological revolution that has taken place during the last years in research areas like computing, telecommunications, computer networks, remote sensing and global positioning. In particular, the appearance of the sensor web enables the sharing of a wide variety of observations from spatially referenced sensors into a distributed computing network (Delin et al., 2001). As a result of the integration of these technologies, quick and automatic alert and characterization of disasters is now achievable.

The design of appropriate emergency procedures, however, is only possible if decision makers are able to retrieve relevant (usually distributed) information with right format and resolution, any time, wherever they are. In other words, some kind of Decision Support System (DSS) is required. In this sense, Multicriteria Decision Analysis (MCDA) procedures can reveal decision makers' preferences and systematically incorporate them to a Geographic Information System. Spatial MCDA can be defined as a collection of techniques for analyzing geographic events where the results of the analysis depend on the spatial arrangement of the events.

In this paper, the web service-based architecture of a framework for decision support in natural disasters management is presented. The architecture incorporates a collection of general purpose web services that collaborate in the implementation of MCDA procedures. Research needs related to both well known OGC specifications and other required services were also identified during the design of the architecture. The remainder of this paper is organized as follows. Next section is devoted to Multicriteria Decision Analysis. The architecture of the framework is briefly described next. Then, the research needs identified during the design of the architecture are briefly illustrated. The forest fire risk assessment in Galicia is next presented as a possible real application of the framework. Finally, some conclusions are drawn.

MULTICRITERIA DECISION ANALYSIS

In words of Malczewski, "decision analysis is a set of systematic procedures for analyzing complex decision problems. The basic strategy is to divide the decision problem into small understandable parts; analyze each part; and integrate the parts in a logical manner to produce a meaningful solution" (Malczewski, 1999).

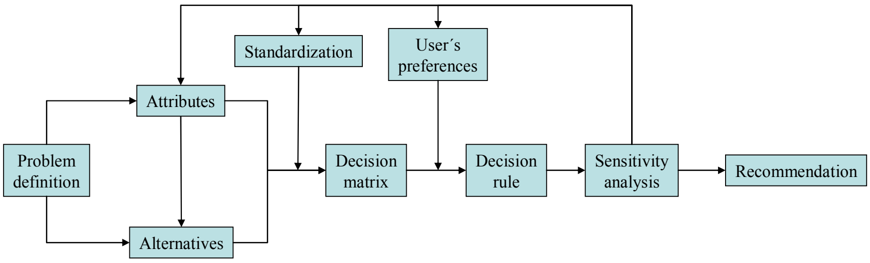

Figure 1: A typical MCDA sequence

Typically, procedures for managing natural disasters consider multiple conflicting spatial and non-spatial criteria. A large set of feasible alternatives is evaluated by a number of decision makers, who are often characterized by individual preferences. MCDA problems involve five major components: (1) a goal the decision makers attempt to achieve; (2) the decision makers; (3) a set of evaluation criteria (objectives and attributes) on the basis of which alternative courses of action are evaluated; (4) the set of decision alternatives; and (5) the set of outcomes associated with each alternative-attribute pair. From a GIS viewpoint, attributes are recognized as thematic layers, alternatives as the entities (pixels for the raster data model, points, lines and polygons for the vector data model) that define those layers, and outcomes as the values (one per layer) associated with each entity.

Assuming a direct correspondence between attributes and objectives, the MCDA problem becomes a Multiattribute Decision Making (MADM) problem. The MADM approach suits evaluation problems (such as risk assessment) and is best undertaken using the raster data model. Figure 1 shows a typical sequence of the involved activities in spatial MCDA.

In this sequence, we have to highlight four critical steps: problem definition, where relevant factors are identified and a set of layers is accordingly defined; standardization of layers, in order to transform all attributes to a common scale before an aggregation is made; inclusion of user preferences, expressed as relative importance weights assigned to the evaluation criteria; finally, aggregation of criteria by means of a decision rule, i.e., a final score is assigned to all alternatives.

Although MADM provides the decision makers with a general skeleton to systematically insert their subjectivity in any evaluation problem, multiattribute techniques have usually been implemented as ad-hoc solutions to specific problems. These solutions are inherently non-interoperable.

A FRAMEWORK BASED ON OGC SPECIFICATIONS

The service-based framework's architecture (see Figure 2) is based on the three-tier Logical Architecture of the OGC. Beyond the implementation of well known OGC specifications, the architecture includes: i) general purpose services whose required functionality is outlined in the present paper and ii) other services whose functionality depends on specific risk management applications, such as snowfalls, forest fires and oil spills. Each of the three tiers of the proposed architecture is briefly described below.

Information Management tier: It is responsible for the management of alphanumeric and geographic data. GIS Data Services include the well known OGC Web Feature Service (WFS) (OGC-WFS, 2002) and Web Coverage Service (WCS) (OGC-WCS, 2003), whose functionality enables the uniform access to heterogeneous vector and raster data sources, ranging from simple vector GML files and raster files to complex spatially enabled DBMSs, such as Oracle, DB2, Informix and PostGIS, and complex Raster Management Engines such as Grass and Idrisi. The services of the Sensor Web Framework enable the integration into the system of the observations measured by a collection of sensors (see next Subsection). GIS Analysis services provide the framework with general purpose advanced functionality for both vector and raster analysis. In particular, two such services are included, namely, the Vector Spatial Analysis Service (VSAS) and the Raster Spatial Analysis Service (RSAS). Roughly speaking, the former enables the application of vector operations, such as those proposed by the OGC Simple Features – SQL Specification (SFS)(OGC-SFS, 1999), to features retrieved from WFSs. Similarly, the later enables the application of raster operations such as those proposed in (Tomlin, C.D., 1990), to coverages obtained from WCSs. A more detailed description of the required functionality of these two services, not considered by the OGC, is given next section.

Processing tier: It is responsible for the processing of large amounts of data. The Multicriteria Decision Analysis service (MCDAS), which implements the MCDA techniques described in the previous section, is the main general purpose component of this tier. The functionality of this service is described in depth in next section.

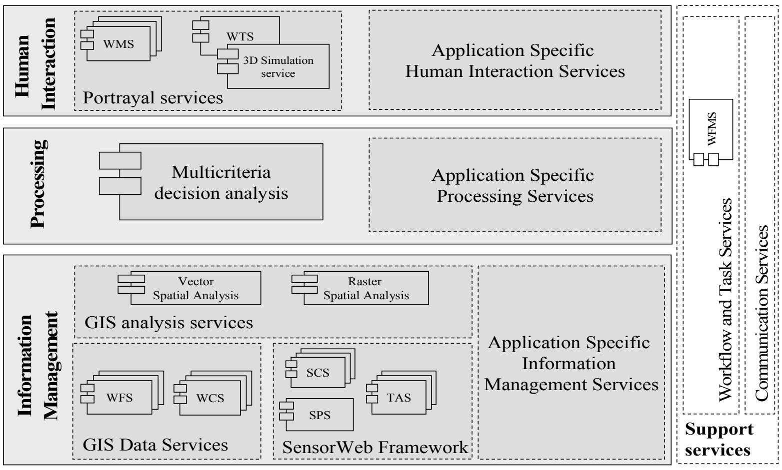

Figure 2: Architecture of the Framework

Human Interaction tier: It is responsible for the interaction with the end user. It includes well known portrayal services proposed by OGC, such as the Web Map Service (WMS) (OGC-WMS, 2004), and also specific services for implementing the user interface of the relevant application.

Other support services not included in any of the aforementioned tiers are usually required. These services include Workflow and Task services and Communication services. The former perform tasks related to the chaining of other services and the later are in charge of the encoding and transferring of data across the communication networks.

Sensor Web Framework

The functionality required to discover available sensors, determine their capabilities, schedule and access their observations and receive alerts under specific conditions is crucial for an effective risk assessment. Any design strategy must be widely applicable and robust against evolutionary change of involved technologies. In contrast to the traditional proposals based on distributed objects (CORBA, COM, RMI, etc.), Webn services allow to adapt easily to evolving requirements and functionality and to make accessible their functionality in heterogeneous computing environments (Rennolls et al., 2004). This open and interoperable technology has inspired the OGC proposals for building a unique and revolutionary platform for exploiting Web-connected sensors, called Sensor Web Enablement (Botts, 2004). An example of the application of this technology in the integration of the traffic web cams of the City of Ottawa is presented in (Liang et al., 2005).

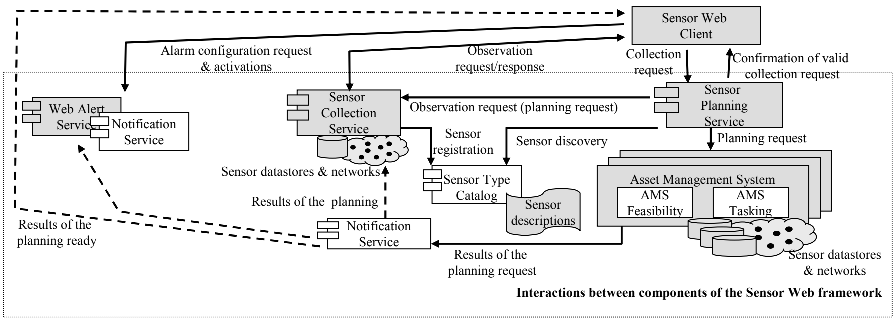

Figure 3: Sensor Web framework

Figure 3 shows our proposal for a distributed framework based on OGC Sensor Web specifications. Grey boxes denote OGC services for accessing and planning sensor observations and alerts. White boxes denote services that control the interaction between the other services. Broadly, the framework behaves as follows. Initially, the OGC Sensor Planning Service (SPS) (OGC-SPS, 2003) assists the client in preparing its collection planning and checks whether such a planning can be handled by some existing *Asset Management System* (AMS). The selected AMS identifies, uses, and manages available information sources and sensor networks in order to meet the client information collection goals, and finally, when the observation results are ready, they are disseminated to consumers by a *Web Notification Service* (WNS) (OGC-WNS, 2003). Examples of consumers are *Sensor Collection Services* (SCS) (OGC-SCS, 2002), *Web Alert Services* (WAS) (OGC-WAS, 2003) and OGC enabled clients. Despite of its limitations (see next section), the standard web interface of the SCS enables the uniform access to the data of a great variety of sensor types required for the management of natural disasters. A *Sensor Type Catalog* (STC) is used by the SCS to access the specific capabilities of each available sensor. Such capabilities may next be used by a Web-enabled client to request observations from the sensor. To ensure the interoperability between different Web-enabled participants, observations are encoded using standards such as *Sensor Model Language* (SensorML) and *Observations and Measurements Schema* (O&M).

In addition to the functionality available to query the data measured by the sensors, a *Web Alert Service* (WAS) (OGC-WAS, 2003) allows the clients to define alerts on the sensor data. Such alerts trigger actions when particular conditions on the data are met. It should be remarked that due to delays in the acquisition of sensor observations and other network problems, the notification of the activation of these alerts should be done in an asynchronous mode, by a WNS.

Multicriteria Decision Analysis Service

The expected functionality of the MCDAS is now briefly described. First it receives as request the definition of a MCDA procedure in some XML-based MCDA specification language. Such a procedure declares the data sources to be used and the operations to be applied to the data of those data sources, in order to obtain the final result. This final result is a raster coverage that assigns a risk value to each of its cells and it is included in the response of the MCDAS in some of the supported coverage formats, such as GML and GeoTIFF. To access the data sources and apply the required vector and raster operations, the MCDAS makes use of the general purpose functionality supplied by the services of the *Information Management tier*. The interaction of the MCDAS with those services is illustrated in Figure 4. More precisely, a MCDA procedure sent to the MCDAS consists of the following four steps:

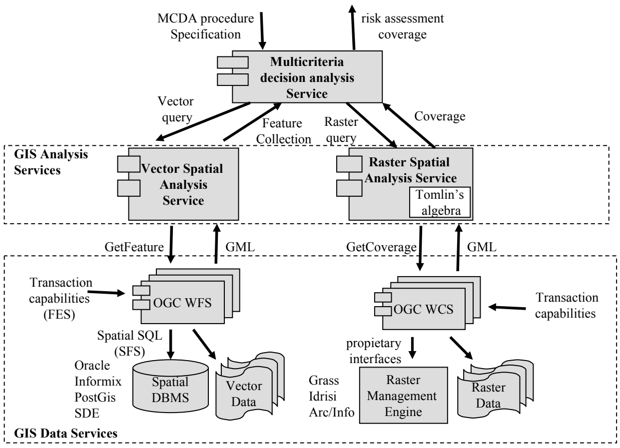

Figure 4: Multicriteria Decision Analysis Service

1. *Problem definition*: It consists of specifying which data sources provide which data and in which format. These data may either be directly accessible from some data source or indirectly computed by operations of GIS Analysis services (VSAS and RSAS). Thus, for example, a problem definition may include the following: i) Vector features from some features collection retrieved from some WFS. ii) Vector features obtained as a result of vector operations, such as spatial intersection, spatial buffer, etc. These operations may be executed by some VSAS. iii) Raster coverages retrieved from some WCS. iv) Raster coverages obtained as a result of some raster operations, such as interpolations, filters, enhancements, etc. The results of these computations may also be recorded in relevant data sources by means of transactional WFSs and transactional WCSs.
2. *Standardization*: A standardization technique from a list of available procedures (maximum score, score range, etc.) is selected to transform the data specified in the previous step to a common scale. This transformation is expressed in terms of vector and raster operations available in the general purpose GIS Analysis Services (VSAS and RSAS).
3. *User's preferences*: A choice between several procedures (ranking, rating, pairwise comparison, trade-off analysis, etc.) allows the decision maker to associate a relative importance weight to each normalized layer.
4. *Aggregation*: A decision rule (simple additive weighting, ideal point, concordance methods, etc.) is finally used to aggregate all the coverages resulting from the previous step into a resultant coverage. Again, required operations are provided by the VSAS and the RSAS.

RESEARCH NEEDS

Based on the description of the framework's architecture given in the previous Section, pieces of work that need relevant research are now identified. These research needs include both the definition of new GIS Web Services and the revision of already existing OGC specifications.

Required GIS Web Services not Considered by the OGC

The web services required for the framework that are not considered in any of the OGC specifications are the following.

Vector Spatial Analysis Service (VSAS): The functionality provided by the OGC WFS specification restrict to the retrieval of the features, from a given feature collection, for which specific spatial and/or non-spatial conditions hold. However, more advanced vector spatial analysis operations are required to achieve the functionality required by MCDA procedures. Good examples of these operations are those included in the OGC SFS (OGC-SFS, 1999). A Vector Spatial Analysis Service (VSAS) is required and therefore relevant research for its design and implementation is identified here as a need. The VSAS must receive as a request a spatial query in some spatial query language. Then, an execution plan must be built to obtain the final result. Such a result should be encoded in GML. Research is therefore required both in the formalization of the spatial query language and also in the definition of efficient query processing techniques. In these authors opinion, a good candidate for a spatial query language is a spatial extension of the XML query language XQuery. It is also estimated that aforementioned research is not going to be too complex, since relevant pieces of work have already been done for SQL at both logical level (Viqueira et al., 2004) and physical level (Kriegel et al, 1993; Gaede et al, 1998). A spatial query language for GML can already be found in (Córcoles et al, 2001).

Raster Spatial Analysis Service (RSAS): The functionality given by the OGC WCS specification lacks expressive power to perform raster spatial analysis. A well known set of operations for this purpose is the one proposed by Tomlin (Tomlin, 1990). Required operations on raster coverages can also be found in the OGC Grid Coverages Specification (OGC-GC, 2001) and in the area of remote sensing. A Raster Spatial Analysis Service (RSAS) is therefore required to support all the aforementioned operations. Thus, research is also needed to end up with a good design and efficient implementation. In particular, research is needed on the formalization of a raster algebra and relevant query language (ideally an XML-based query language). Notice that contrary to vector data, few research efforts were devoted to the formalization of the management of raster data. Research is also required at the physical level to achieve an efficient implementation of the operations. Initial approaches to be studied are (Widmann et al, 1997; GRASS, 2005; MFWorks, 2005; Lorup, 2000; MapCalc, 2001). Finally, the new GML3 is a good candidate for the representation of the raster coverages received and produced by the RSAS.

Multicriteria Decision Analysis Service (MCDAS): The functionality of this service and also its collaboration with the services of the *Information Management Tier* of the proposed architecture were already presented in the previous section. It is reminded, that MCDA procedures are defined in some *XML-based MCDA Specification Language*, in a similar manner that maps are defined in the Styled Layer Descriptor (SLD) in a WMS. Research is therefore required for the formalization of such an XML-based language and also for the efficient implementation of the service.

A Critical Revision of Existing OGC Specifications

Regarding the revision of already existing OGC specifications, the following research needs are identified.

Web Feature and Web Coverage services: The need for a VSAS was already identified in the previous subsection. It was also stated that the functionality of such a VSAS could perfectly match the one defined in the OGC SFS, which also match the spatial part of the ISO SQL Multimedia (Ashworth, 2002) and which is implemented in various commercial and open source DBMSs. It can be trivially assumed that spatial data is going to be processed more efficiently from within a spatial DBMS than from the VSAS, since the DBMS is closer to the data. Therefore, in case a spatial DBMS exists, the spatial operations should be delegated from the VSAS through the WFS and executed in the spatial DBMS. However, such a delegation of functionality is not possible with the current state of the OGC WFS specification. In these authors opinion, this specification should be slightly updated in order to allow such a delegation. In particular, the behaviour of the WFS should be as follows. First, the VSAS receives a request to apply some spatial operation. The VSAS uses the Get Capabilities operation of the WFS to know whether a spatial DBMS exists below it and therefore whether spatial operations can be delegated. In case this is so, the spatial XQuery statement would be passed directly from the VSAS to the WFS. The WFS would transform such a spatial XQuery to the spatial SQL of the DBMS, for them to be executed there. Notice that research results on such transformations were already investigated for conventional queries (DeHaan et al., 2003). Following a similar reasoning, a WCS should also be able to delegate raster spatial analysis operations to a Raster Management Engine such as Grass, Idrisi, ArcInfo Spatial Analyst, etc.

Sensor Planning and Sensor Collection services: Due to the complexity that a collection request from a client may reach and that each AMS may have its own different interface, a standard XML-based language to specify collection requests should be defined as a part of the SPS specification. Such language has to be expressive enough to specify complex collection requests involving various AMSs. Service-composition techniques should be used to ease the concurrent interaction with many AMSs. Regarding the SCS, it is estimated that spatial query functionality should be incorporated in its query language, probably based on the the OGC Filter Encoding Specification (OGC-FES, 2001).

Web Alert Service: This specification is one of the most immature OGC proposals in the Sensor Web context. It requires the definition of a rule-based syntax for describing alerts and a model of extended Web-service able to support pushing capabilities for announcing client alert activations. For this purpose, authors are exploring the capabilities of the standard Rule Markup Language, RuleML (http://www.ruleml.org/), for describing fire alerts on the basis of relevant sensor data, as well as the application of knowledge engines, such as a Jess (http://herzberg.ca.sandia.gov/jess/), to interpret and execute them. An important restriction has been identified as a result of an initial investigation. In particular, spatial conditions and spatial reasoning are considered neither by RuleML nor by the implementation of Jess. Notice however that such spatial capabilities are interesting for restricting the activation of rules to facts that happen in specific spatial regions.

Web Notification service: Nowadays the only asynchronous messaging service specified by OGC has some important restrictions: 1) message notification is restricted to a peer-to-peer interaction style and 2) it considers only a centralized notification. More flexible notification protocols and topologies are required to avoid problems such as fault tolerance and inefficiency in highly dynamic and cooperative contexts (such as the Sensor Web). In these authors opinion and on the basis of their previous experiences in Web services coordination (Álvarez et al., 2003), this specification should be revised based on general purpose asynchronous messaging techniques and standard Internet message brokers, such as WS-Coordination (http://www-128.ibm.com/developerworks/) and WS-Composite Application Framework (http://developers.sun.com/techtopics/webservices/).

Web Map Service: It is claimed that the Styled Layer Descriptor (SLD) used to define maps in a WMS should allow the portrayal of geographic data provided by any kind of GIS Web Service, for example, from a MCDA service or the sensor data retrieved by the Sensor Web services.

APLICATION TO RISK ASSESSMENT IN GALICIA

Every year, as a result of many environmental, climatic, human and socio-economic factors, thousands of hectares of forest land are burned by wildfires in Galicia (NW Spain). The way the proposed architecture may be applied to fire risk assessment in Galicia (Varela et al. 2003) is illustrated next.

Our purpose will be to build a propagation risk index from the set of involved factors: land slope, natural and artificial firewalls, fuel models, temperature, wind speed and humidity. Let us see how the MCDA service may drive all the process.

First, since slope is a structural attribute for any given zone, this layer is likely to be directly stored in a raster dataset. If this information is not currently at hand, then the RSAS may cooperate with the WCS to originate it from an existing Digital Elevation Model (DEM). Even a DEM may be interpolated from mass points and contours retrieved by the WFS. As stated by experts, whenever possible, fire managers could let fire advance towards a firewall a maximum of 100 metres. The RSAS may create a proximity raster from vector firewalls. Fuel models, may be rasterized from a polygon data set. Finally, the meteorological information provided by a network of 24 weather stations is gathered in real time by the Sensor Web services and routed to the RSAS. Here, one dataset per parameter is interpolated.

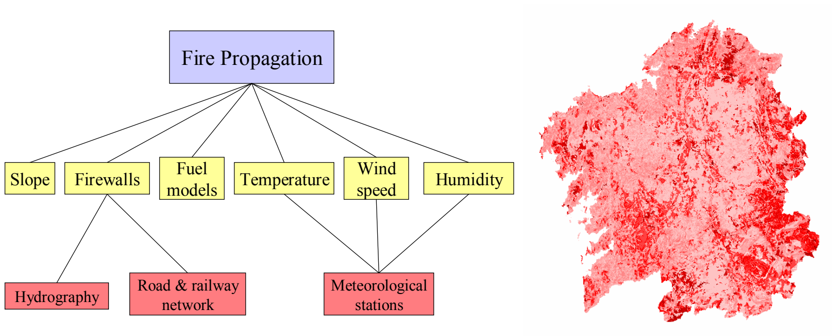

Figure 5: A fire propagation example and the resulting risk index

Once the problem has been defined, three main steps must be chained: the standardization must take into account that slope is a benefit criterion and relative humidity is a cost criterion; next, each layer is weighed using the procedure selected by the decision maker; finally, a decision rule aggregates all standardized, weighted layers. Thus, a single layer which assigns a risk score to each alternative (pixel) is produced. Now a WMS may deliver this result to the clients (see Figure 5); here, the darker shades reveal a greater risk.

CONCLUSIONS

The architecture of a service-oriented framework for the management of natural disasters was presented. General purpose services provide functionality for the application of MCDA techniques to available geographic data, obtaining as a result an assessment of a particular risk (forest fires, oils spills, etc.) at each point of a given area. The application of this functionality to a real scenario (fire risk in Galicia) together with the research experience of the authors in MCDA techniques, databases and distributed software architectures helped in the identification of research needs related both to the revision of current OGC specifications and to the development of new services. Pieces of further work are therefore the following:

- The formalization of an extension of XQuery for the management of vector spatial data.
- The investigation on query processing techniques for the above spatial XQuery language.
- The formalization of an algebra and query language for the management of raster coverages.
- The investigation on query processing techniques for the above raster query language
- Extension of the interfaces of the OGC WFS and WCS to achieve the possibility of delegation of spatial functionality to spatial DBMSs and raster engines, respectively.
- Revision of the OGC Sensor Web proposal. In particular, the interface of the SPS should be homogeneous and hide the complexity of the heterogeneous AMS. The WAS operations and its rule-based syntax must be defined. The WNS should support a new interaction model to be a useful tool for Web-service integration.

- The investigation on the efficient communication of vector and raster data (basically GML) between web services. Such investigation should include relevant research on compression techniques and caching mechanisms.
- Implementation of a first prototype.

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