

## Interacting with Spatial Data Warehouses through Semantic Descriptions\*

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**Abstract.** *Users with limited GIS and BI skills usually have troubles to interact with spatial data warehouses. This paper proposes a knowledge-based GUI to help these users to find data marts related to domain specific keywords, understand their contents, and do spatial information analysis. The proposed GUI presents ontological descriptions of the structure, contents, and information analysis capabilities of the data marts. It supports the selection of spatial operators and aggregation functions to compose SOLAP queries. The tables, graphs and maps presented in response to these queries allow further user interaction to gradually refine the analysis. An empirical usability test has been applied to the proposed GUI, in a case study for the agriculture domain, and the results suggest that it meets the user's needs.*

### 1. Introduction

Decision support in areas such as management of natural resources, agriculture, and disaster prevention often requires the analysis of large volumes of spatial data. A spatial data warehouse (SDW) can help to resolve this kind of demand [Rao et al. 2003, Malinowski and Zimányi 2007, Bimonte et al. 2008]. It extends the capabilities of a traditional data warehouse (DW) for handling large volumes of numeric and categorized data in the dimensional model, such as on-line analytical processing (OLAP), with abilities of typical geographic information systems (GIS) for handling spatial data. The goal is to facilitate the analysis of different kinds of data, and present results in maps whenever it is considered appropriate.

Spatial objects can appear in spatial data as members of dimensions (e.g., multi-polygons representing states and cities) and as measures of fact tables (e.g., geographic locations of cases of poisoning by pesticides) [Malinowski and Zimányi 2007]. In addition to the dimensional model and the traditional OLAP operators and aggregation functions, a SDW must support spatial data types integrated to the dimensional model [Fidalgo et al. 2004], and a variety of methods for handling spatial objects [Silva et al. 2008].

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This work focus on the development and usability test of the graphical user interface (GUI) of an ontology-based system for interacting with SDWs called  $S^2DW$  (Semantic and Spatial Data Warehouses). It allows ordinary users to search for spatial data marts, using domain specific keywords, and do spatial information analysis by interacting with the recovered semantic descriptions of spatial data marts. These semantic descriptions are built in accordance with a spatial dimensional model, described in the SDW ontology. This ontology defines the possible structural components, operators, and aggregation functions available in the data marts. It describes the possible connections of the structural components of spatial data marts and the possible uses of operators and functions. These concepts are used in conjunction with terms taken from a domain ontology, for semantically describing spatial data marts according to domain specific knowledge.

A spatial data mart is presented in the proposed knowledge-based GUI as a graph. The GUI allows the user to explore the structure and contents of the data mart. It also assists the user to correctly assemble operators, compatible with the types of the selected members of the dimensions and measures of the fact table, to compose spatial OLAP (SOLAP) queries. The query results can be viewed as tables, graphs and maps. Then the user can interact with these results in order to refine his information analysis.

### 1.1. Related Work

The research problems being currently considered in spatial data warehouses include: (i) SDW modeling [Fidalgo et al. 2004, Malinowski and Zimányi 2007]; (ii) extracting, transforming and loading (ETL) spatial data into a SDW [Skoutas and Simitsis 2006, Martino et al. 2009]; and (iii) human-computer interfaces to support user interactions with spatial data marts for doing information analysis [Rao et al. 2003, Sell et al. 2008, Xie et al. 2007]. This paper addresses the third problem.

Some proposals from the literature use ontologies and semantic annotations to help users to explore a DW and make information analysis [Sell et al. 2008, Xie et al. 2007]. However, these approaches do not address spatial data. The correct use of the variety of spatial operators and spatial aggregation functions available for information analysis in a SDW requires knowledge about their functioning, inputs and outputs.

[Sell et al. 2008] use ontologies and inference to integrate business semantics with the dimensional data, in order to support information analysis services. In [Xie et al. 2007] IT specialists use an extension of OWL to build mappings between the schema of a DW and domain specific terms used in information analysis, in order to allow domain users to specify their analysis needs and automatically generate data marts to meet them. However, none of these studies present visual interfaces for the user to perform dimensional queries involving manipulation of spatial objects.

The rest of this paper is organized as follows. Section 2 presents a SDW about farms and agricultural production that serves as a case study. Section 3 describes the  $S^2DW$ 's architecture, the SDW ontology, and an example of domain ontology for agriculture. Section 4 presents the  $S^2DW$ 's knowledge-based GUI and shows how the user can interact with this GUI. Section 5 describes some experiments that were performed to assess the usability of the proposed GUI, and analyzes the results. Finally, Section 6 presents the conclusions, and some topics for future work.

## 2. Case Study: A SDW of the Agriculture Domain

Figure 1 shows a data mart of a SDW about farms activities and agricultural production in Santa Catarina State, Brazil. This SDW has been produced with data from Epagri (Agricultural Research and Rural Extension Institute of Santa Catarina). The fact table includes the scalar measures *PlantedArea*, *HarvestedArea*, *AmountProduced*, and *FarmsCount*, along with the spatial measure *FarmHeadquarter* (geographic coordinates of farms' headquarters). Such measures are grouped according to levels and members of the dimensions *Place* (with geographic objects representing the *State*, its *Regions*, *Cities*, and *WaterBodies*), *Time*, *Agricultural Product*, and *Farm Properties*.

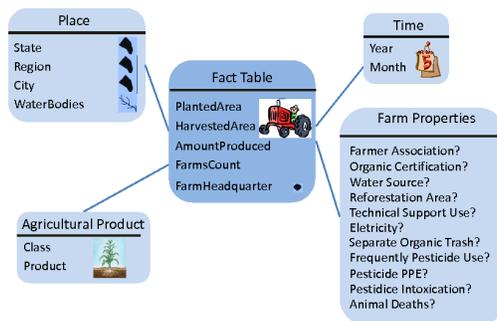


Figure 1. SDW about farms activities and agricultural production

This data mart supports SOLAP with conventional and spatial data. The multipolygons of the spatial dimension *Place*, can be used in spatial operations to select, group and aggregate data. The results can be presented as tables, graphics or thematic maps. Aggregation of the spatial measure *FarmHeadquarter* can generate subsets of the respective geographic points (e.g., a subset of points that are inside each county) or other geometries (e.g., a Voronoi diagram), depending on the aggregation function chosen among those available for this particular type of spatial data. Different aggregations of spatial measures can reference the same spatial object representation, in order to avoid copies of potentially large representations of spatial objects.

Ordinary users have additional difficulties to interact with SDWs due to the great variety of methods used to manipulate spatial objects. In the following section we present our proposal to facilitate this interaction.

## 3. The $S^2DW$ System

$S^2DW$  (Semantic and Spatial Data Warehouses) is a system to support information analysis in SDWs [Deggau and Fileto 2009]. It aims to enable the ordinary user to identify spatial data marts related to a topic of interest and pose SOLAP queries on this data mart through a knowledge-based GUI. Additional interactions can be performed on the results of the queries in the form of tables, graphs and maps, in order to refine the analysis.

Figure 2 illustrates the architecture of the  $S^2DW$  system and highlights the function of its knowledge-based GUI. The semantic descriptions of spatial data marts refer to the SDW ontology and the domain ontology. The former ontology is fixed and includes conceptual definitions of structural components of spatial data marts (dimensions, levels,

measures) and their relationships, in addition to the description of operators and aggregation functions for data manipulation in SDWs. The domain ontology, which varies with the application domain, allows the description of the contents of data marts by using domain-specific knowledge and vocabulary. The  $S^2DW$ 's GUI provides a graphical view of the knowledge contained in the domain ontology and the semantic descriptions of data marts. It enables the users to explore and use the information analysis capabilities of these data marts by themselves.

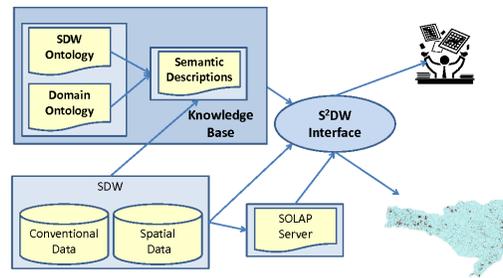


Figure 2. The  $S^2DW$ 's general architecture and knowledge-based GUI

### 3.1. The SDW Ontology

The SDW ontology describes the possible structural compositions and data manipulation facilities in a spatial data mart accessed via  $S^2DW$ , according to the dimensional model with spatial extensions from [Fidalgo et al. 2004]. Figure 3 gives a high level view of the hierarchy of concepts of the SDW ontology<sup>1</sup>. It is divided into four portions: (A) the structural components of spatial data marts; (B) the types of spatial entities; (C) the data handling operators used to filter and group information according to the descriptive members of the dimensions; and (D) functions to aggregate measures of fact tables.

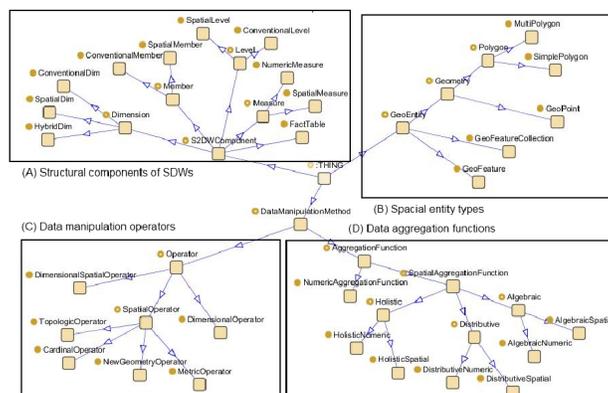


Figure 3. A general view of the SDW ontology

This version of the SDW ontology uses the classification of spatial operators and spatial aggregation functions from [Silva et al. 2008], but the SDW ontology can be adapted to describe other collections of operators and functions.

<sup>1</sup>For simplicity we omit several details of the proposed ontologies. We only present ISA relationships (subsumption hierarchies) and the concepts that are close to the top of the hierarchies.

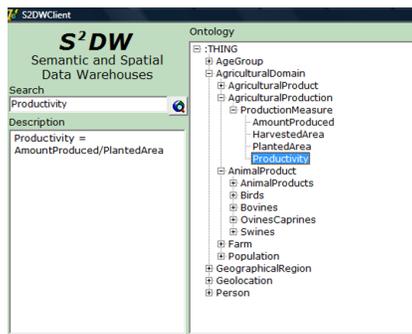


Figure 4. Keyword-based search and navigation on a domain ontology

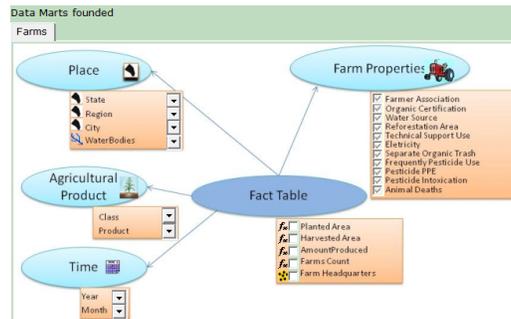


Figure 5. Graphical rendering of the semantic description of a spatial data mart

### 3.2. A Domain Ontology for Agriculture

$S^2DW$  is domain independent. It can be adapted to different domains by replacing the domain ontology. As such ontology formalizes specific domain knowledge, it enables the system to present data marts, receive and process queries, and present results according to specific domain vocabulary. It facilitates the interactions of users from that particular domain with the SDW. In this work we used an agriculture ontology, which has a small portion of it illustrated on the right side of Figure 4, to describe and facilitate interaction with the SDW about farms and agriculture production.

## 4. The $S^2DW$ 's Knowledge-Based GUI

Figure 4 shows the initial screen of  $S^2DW$ . This screen includes an input field for entering keywords on the top left corner, and a hierarchical view of the domain ontology on the right side. The user starts using the system by entering one or more keywords or browsing the view of the domain ontology to choose keywords referring to a subject of interest. The text field on the left bottom side of the window presented in Figure 4 provides information about the posed keyword, taken from the knowledge-base. When the user has finished the indication of subjects, he asks the system to perform a semantic search for data marts with information related to that subject, by clicking on the *Search* button or pressing *Enter*. The user's interactions with the  $S^2DW$ 's knowledge-based GUI, follows the sequence of steps described below.

1. search for data marts related to a subject;
2. pose one or more SOLAP queries to the recovered data marts:
  - (a) select measures, members of dimensions to filter and aggregate these measures, sequences of operators to filter data, and aggregate functions to consolidate data;
  - (b) request the execution of the query, by pressing the button *View Results*;
  - (c) visualize the results in tables, graphs and/or maps;
  - (d) if necessary, refine the information analysis by interacting directly with the presented results (back to the beginning of step 2).

In the following we illustrate this interactive process by means of examples from a case study for the agriculture domain.

#### 4.1. Searching for spatial data marts related to a subject

Suppose the user is interested in analyzing the use of pesticides by farms and its possible impacts on water supplies. If he has any number of simple or composite keywords in his/her mind to express the subject of his concern (e.g. “agrotoxin”), he can provide them, otherwise he can browse the domain ontology view provided by  $S^2DW$ , in order to find and select one or more keywords related to his interests. When he asks for the execution of the search with the provided keywords, the system executes a semantic search [Mangold 2007] on the semantic network formed by the ontologies and semantic descriptions of spatial data marts, using a spreading activation algorithm [Crestani 1997] that takes into account the user’s preferences with respect to particular denotations of keywords [D’Agostini and Fileto 2009]. After processing this search,  $S^2DW$  presents the semantic description of each spatial data mart.

Figure 5 shows the graph representing the semantic description of the data mart from Figure 1 in the  $S^2DW$  knowledge-based GUI. This graph is returned in response to a search for the keyword “agrotoxin”. This keyword is not explicitly mentioned in the semantic description of that data mart. However, the references to the domain concept “pesticide” in the description of the dimension *Farm Properties* made it possible for the semantic search process to recover this data mart description as a response to the search, because the words “agrotoxin” and “pesticide” are related in the domain ontology.

Next, the user can do information analysis with a spatial data mart using the  $S^2DW$ ’s knowledge-based GUI as described in the following.

#### 4.2. Performing Spatial Information Analysis

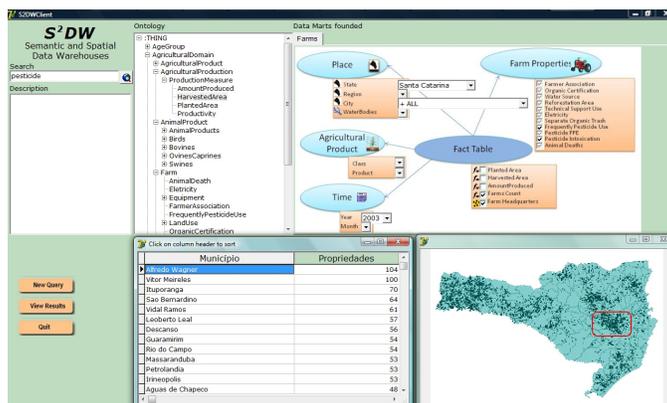
The user must select members, measures, operators and aggregation functions in order to specify a SOLAP query using the  $S^2DW$ ’s knowledge-based GUI. In the following we describe the user interactions for posing and analyzing the results of two example queries.

*Query 1: Show the geographic distribution of the cases of poisoning by pesticides among the farms of Santa Catarina State in 2003*

The user can specify this query by first selecting the spatial measure *Farm Headquarters* and the numeric measure *Number of Establishments*. Then, he could select the value *TRUE* for the feature *Frequent Pesticide Use*, in the dimension *Farm Properties*, in order to indicate the filter condition in this dimension. He could also select the year *2003* in the *Time* dimension, and the state called “Santa Catarina” in the *Space* dimension, in order to indicate the filter conditions in the respective dimensions. The specification of the value *ALL* for the level *City* indicates that the measures must be aggregated by city. The operator *GeoIntersects* and the aggregation function *Collection* are taken as default when the user selects a spatial members and a spatial measure, respectively. After finishing the desired selections, the user press the button *View Results*. Figure 6 illustrates the selected items (the graph in the top left side) and the results returned for this query (the pivot table and the map in the bottom).

*Query 2: In the city with the highest number of properties that use them frequently, list the headquarters of farms that are close to the major river.*

The municipality with the highest incidence of poisoning by pesticides, *Alfredo Wagner*, can be easily identified in Figure 6. The user can select it, by clicking on the top



**Figure 6. Geographic distribution of the farms with cases of poisoning by pesticides and that make frequent use of pesticides in Santa Catarina State in 2003**

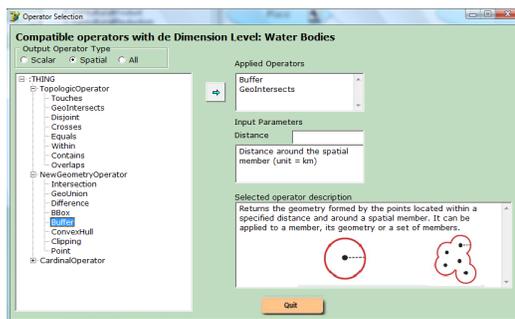
city name in the pivot table, or on the representation of the municipality highlighted by a bounding rectangle in Figure 6. Then, the user can further refine his analysis, in order to assess the risk of contamination of *Water Bodies* close to the farms of this city. For doing this, he can zoom-in and reposition the map to focus in the surrounding of the *Itajaí do Sul River*, which is a major water body that crosses the municipality of Alfredo Wagner. The river can be selected by clicking on its representation on the map or by choosing it in the *Water Body* level of the *Space* dimension. Then, the user can click on the icon of the corresponding dimension level, in order to verify the existing operators that can be used to filter information from the fact table, using the spatial objects of the type *Water Body*. This is determined by an inference in the ontology and the semantic descriptions of the data mart. The allowed operators are presented in the dialog box of Figure 7. The explanations accessed by clicking on the respective operator name help the user to find out that he can apply the *Buffer* operator, providing a value for its distance parameter, in order to create an expanded geometry that can be used with the *GeoIntersects* operator to find the farm headquarters that up to 5 kilometers from the *Itajaí do Sul River*. The algorithm below presents the generated SOLAP query in a spatial extension of the MDX<sup>2</sup> language and Figure 8 shows the final results of the analysis in a map on the S<sup>2</sup>DW GUI.

```
SELECT Count ([Measures].[Farm Headquarters]),
           Collection ([Measures].[Farm Headquarters])
  ON ROWS {[Local].[City]}
FROM FarmsProdSC
WHERE (
  [Farm Properties].[Frequent Pesticide Use].[True] AND
  [Time].[Year].[2003] AND
  buffer( [Local].[Water Bodies].[Itajaí do Sul River], 5 )
  INTERSECTS
  Farm Headquarters )
```

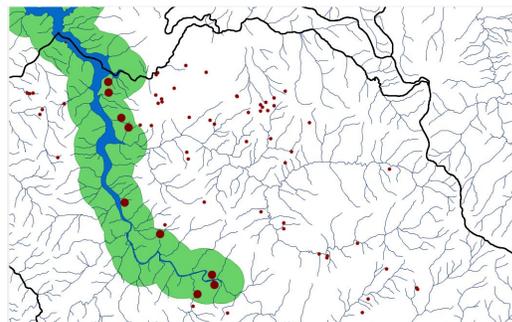
## 5. Usability test of the S<sup>2</sup>DW's GUI

We developed a prototype of the S<sup>2</sup>DW system to analyze the usability of the proposed knowledge-based GUI. It was implemented as a stand-alone application running on Win-

<sup>2</sup><http://msdn.microsoft.com/en-us/library/ms145506.aspx>



**Figure 7. Available operators for filtering information using the spatial member WaterBodies**



**Figure 8. Resulting map after the application of Buffer and the Intersects operators**

dows. We used this prototype to perform some experiments with users from the agriculture domain to assess whether the  $S^2DW$ 's knowledge-based GUI provides an appropriate means for these users to do information analysis. In these experiments we asked the users to do some data analysis tasks on the spatial data mart presented in Figure 1, and assessed their performance on doing these tasks with  $S^2DW$ . We also applied a semi-structured questionnaire to the participants, asking them to answer some questions, in order to assess their opinion about proposed system.

### 5.1. The experimental setting

The experiment used inspection methods in accordance with the norm ISO 9241-11 [ISO/IEC 1991]. The empirical test of usability, also known as observation technique, was chosen as the method of inspection. We used the software Morae [TechSmith 2010] to observe the actions of each user, capture data, and apply the questionnaire. According to [Nielsen 1993], experiments with 6 to 12 users are enough to discover 85% of the usability problems. The experiment was administered to 17 users. The execution of the experiment was divided into three steps, as described below:

**Step 1 - Presentation of the  $S^2DW$  system** We first provided an overview of the information analysis process using  $S^2DW$ .

**Step 2 - Execution of Information Analysis Tasks:** The users were asked to specify some SOLAP queries on the  $S^2DW$  knowledge-based GUI. The sequence of tasks was previously stored as a script in Morae. The user read the instructions before performing each task and indicated when he was able to start that task. At the end of each task, he indicated its conclusion, and the system presented him the next task.

**Step 3 - Application of the Questionnaire:** Upon completion of all the information analysis tasks, Morae prompted the user to answer the questionnaire and give his opinion about doing the proposed tasks with  $S^2DW$ .

Morae collected information about each user's interactions with  $S^2DW$ , including each manipulation of the GUI components, the time spent per task, and the number of mouse clicks per task. We have also recorded the user's behavior on video. The information analysis tasks requested to the users were the following:

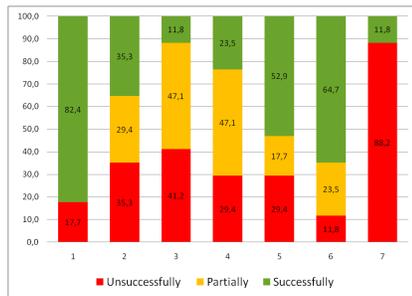


Figure 9. Success per task

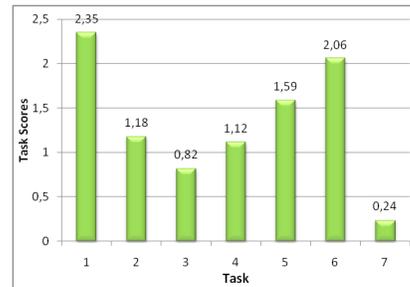


Figure 10. Average score per task

1. Provide keywords or browse the view of the domain ontology in order to find a data mart with information about *agricultural production*.
2. Show the distribution of the *production* of *onions* among the *counties* of *Santa Catarina* state in 2005.
3. Show the distribution of the *productivity* (*production/plantedarea*) of *onions* among the *counties* of *Santa Catarina* in 2005.
4. Identify the *city* with the highest yield of *onions* in 2005, in the table or map resulting from the execution of the previous query.
5. Determine the distribution of *farm headquarters* in the *counties* of *Santa Catarina* that were certified *organic producers* in 2003.
6. Identify the city with the largest number of *farms* certified as *organic producers* in 2003.
7. Identify, in this city, the *farm headquarters* that are less than 5 km from a given geographic point.

## 5.2. Experimental Results

After the execution of the experiment with all users, we manually analyzed the data and video recordings. We assigned a score for the level of achievement of each task for each user, according to the following criteria:

- **Unsuccessful (score = 0):** the user was unable to perform any interaction necessary to perform the task;
- **Partially successful accomplished (score = 1):** the user was able to perform some of the interactions necessary to perform a task;
- **Successful with difficulty (score = 2):** the user was able to perform all the interactions necessary to perform the task, but spending more than 4 minutes; and
- **Successful (score = 3):** the user was able to perform all the interactions necessary to perform the task, spending up to 4 minutes.

Figure 9 presents the percentage of the users with each level of success to perform each task, Figure 10 presents the average score of the users when performing each task, and Figure 11 presents the average time spent by the users to perform each task.

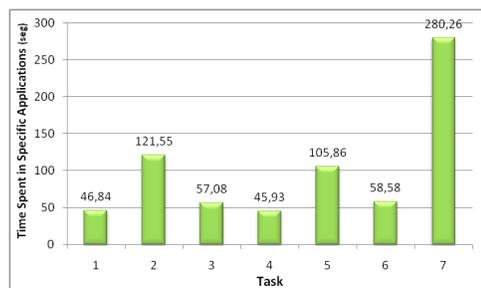


Figure 11. Average time per task

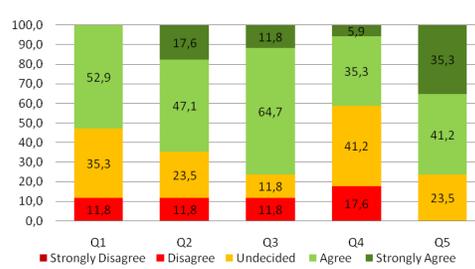


Figure 12. Responses per question

The questionnaire completed by users was composed of the following statements:

1. The proposed interface is clear and easy to understand.
2. The construction of queries is simple and easy to learn.
3. The terms used in the interface are clear.
4. The final results of the queries have been achieved.
5. The interface takes into account the needs of the users.

For each statement above, the user had to choose one of the following scores: (1) Strongly Disagree; (2) Disagree; (3) Undecided; (4) Agree; (5) Strongly Agree. Figure 12 shows the distribution of the users responses for each one of the five questions.

### 5.3. Analysis of the Results

Most users considered tasks 1 and 2 relatively easy. The percentage of users who were “Unsuccessful” to perform the tasks increases for tasks 2 and 3, as shown in Figure 9. Then this percentage decreases, indicating that a learning process has occurred. Task 7 was considered the most difficulty.

The percentage of successful executions of task 3 was one of the lowest. It involves the measure *productivity*, which is not explicit in the fact table, but has to be calculated from existing measures (*AmountProduced/PlantedArea*). This suggests that some support is necessary to define or recover definitions of composite measures.

The average score of task 7 was the lowest one (Figure 10). There were users who did not find the button to check the spatial operators that could be applied. The high quantity of time spent to execute this task suggests that users knew what they wanted. They tried many actions looking for the button to select the spatial operation to be used.

Figure 11 shows a decrease of the time spent with subsequent tasks of the same analysis, except for task 7. Within the refinement of an information analysis, the interface keeps the previous selections, speeding up the procedures to specify subsequent queries. In task 1, which was supposed to be very fast, many users initially posed some quite arbitrary keywords, just to explore the system.

Analyzing the responses provided by users for the questionnaire, one can observe that there is a total or partial agreement of the users with all statements. The only exception was that the users said that some of the desired results were not achieved (negation

of statement 4). However, there was a general agreement that the proposed system meets the information analysis needs of users (statement 5).

## 6. Conclusions

$S^2DW$  employs ontologies to describe the structure, information contents, and information analysis capabilities of SDWs. Spatial data marts are semantically described in  $S^2DW$  by correlating concepts from the SDW ontology with those of a domain ontology. The former, which is domain independent, describes the possible structural components, operators and aggregation functions of a SDW. The latter can be changed in the  $S^2DW$  knowledge base, in order to allow adaptation of the system to different application domains, and support user interactions using domain specific vocabularies.

This paper presented the  $S^2DW$ 's knowledge-base GUI. It provides abstractions to enable the user with limited computational skills to search for spatial data marts containing information about a topic of interest, and perform information analysis on them. It has the following capabilities: (i) semantic search for spatial data marts related to a topic of interest; (ii) present semantic descriptions of the structure and the information analysis capabilities of the spatial data marts of interest, in a knowledge-based GUI; (iii) enable interactions with the data mart through this GUI, assisting the user to correctly use the available information analysis capabilities for posing SOLAP queries on the spatial data mart; and (iv) allow further user interactions with the semantic description of the data mart, and with the results presented for the posed queries in order to support gradual refinement of an information analysis. The benefits of the proposed system apply to conventional DWs, but are magnified in SDWs, due to the variety and the complexity of spatial objects and spatial data handling capabilities.

The results of usability tests of the proposed GUI suggest that it needs some improvements, but meets the user's needs. The users consider the GUI clear and easy to understand. The SOLAP query specification using this GUI is easy to learn and feasible for the majority of the users. Thus, these experiments gave an indication that the development of the proposed system should continue.

The next step of our research is to test and tune alternative formal data structures and algorithms necessary to completely implement the proposed system. Among the facilities that can be included on top of the proposed architecture are natural language interpretation capabilities, rules, and more sophisticated inferences to better advise the users to properly choose and compose the operators for information analysis.

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