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Prototyping an intelligent decision support system for improving urban infrastructures management

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Abstract

This paper describes an intelligent decision support system (IDSS) dedicated to coordinated management of urban infrastructures (SIGIU). This system identifies the data and related treatments common to several municipal activities and defines the requirements and functionalities of the computer tools developed to improve the delivery, performance and coordination of municipal services to the population. The resulting cooperative system called SIGIU is composed of a global planning and coordination system (SYGEC) and a set of integrated operating systems (SYDEX), each of them being associated with a specific urban system (sewerage, waterworks, etc.). In order to support the decision-making process, an IDSS was developed as a knowledge-based system provided with inference mechanisms that enables SYGEC and SYDEX to make strategic choices in terms of technical interventions on municipal infrastructures. The knowledge-based system stores experts' knowledge as well as solutions to past problems. Preliminary implementation results show that SIGIU effectively and efficiently supports the decision-making process related to managing urban infrastructures.

Keywords: Intelligent decision support system; Knowledge-based systems; Urban infrastructures; Complaint management

1. Introduction

The rehabilitation of an urban infrastructure is currently one of the main concerns of municipalities in North America. Urban system management has always been the result of the collaboration of various actors. However, these urban infrastructures currently have more constraints due to the transfer of responsibilities as well as the decrease of human and economic resources. Nowadays, only a concerted effort among the groups that participate in urban infrastructure management and continued monitoring will allow the rehabilitation of the infrastructure.

The planning, design and operation of urban infrastructures and urban services is an ever-increasing complex activity. The population asks for top quality services at the lowest possible cost.

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Today, three areas are and will remain for the next decade, of up most concern in the management of urban infrastructures; those areas are the restoration of the quality of the urban environment, the management of large and complex systems and the preventive maintenance and rehabilitation of existing infrastructures. The integration of new technologies constitutes the principal challenge facing urban engineers and urban managers. Throughout this integration, new tools and eventually, new ways of "doing things" in municipal organizations will be implemented, thus, contributing to new solutions to better urban infrastructures management, specially, towards those specific three areas. Without integration of new technologies, meeting the challenges of the future in the management of urban systems would be very difficult (Huber, 1990; Pierre et al., 2001a,b).

Currently, at the planning level, the maintenance level or the rehabilitation level, decisions are frequently made without consulting all stakeholders. The integration of automated tools is not common for the completion of daily activities. Furthermore, the developers of urban system management applications have not embraced the concept of integration. These applications are generally proprietary applications, making their adaptation as well as data exportation, quite costly. Likewise, much of the data cannot be transferred to other applications making their use quite limited for the decision-making process. Therefore, reuse and integration of these tools are very difficult.

On the other hand, since the inception of the theory of multi-agent systems (MAS) there has been a growing interest in studying and modeling the behavior of various agents that collaborate to solve a problem or to carry out a specific task. Distributed problem solving and collaborative decision-making are perhaps the paradigm example of activity in multi-agent systems. This occurs when a group of logically decentralized agents cooperate to solve problems that are typically beyond the capabilities of any individual agent (Wooldridge, 1998; Jennings et al., 1998; Durfee et al., 1991). The application of intelligent systems for data interpretation and condition monitoring is an advancing research field. In recent years, autonomous intelligent agents and multi-agent systems have gained much attention within different real time applications (Jennings et al., 1998). A variety of intelligent techniques have been applied in plant monitoring, which resulted in the development of centralized approaches for condition monitoring, e.g. model-based reasoning systems (McArthur et al., 1996), case-based reasoning system (Warwick et al., 1997), artificial neural networks (Booth and McDonald, 1998). These approaches tend to be fixed, so they lack flexibility and extensibility. Moving to an agent-based architecture allows simultaneous complex tasks to be performed in real time; better handling of inaccurate data is achieved and each agent can be independently updated. For example, Mangina et al. (2001) introduces a hierarchical decentralized multi-agent architecture developed for data interpretation and condition monitoring applications. In Albers et al. (1999) multi-agent and knowledge-based systems have been used to design an Electronic Market Place, or in Brazier et al. (1999) where the multi-agent systems have been used to design and support a call center.

An intelligent decision support system (IDSS), as its name implies, is used to support decision-making and is not intended to replace the decision maker. In fact, an intelligent decision support system (IDSS) works under the assumption that the decision maker is familiar with the problem to be solved and the data required for its solution. The IDSS itself simply supports the examination of alternatives. Hopefully, performance can be improved through a "what if" analysis since the computer-based IDSS speeds up such analysis and related calculations. The typical approach to decision-making follows these procedures: specify the objective or problem; obtain data; generate alternatives; evaluate alternatives; select an alternative; implement the selected alternative and obtain feedback on the implemented alternative.

An IDSS is an interactive system, flexible, adaptable and specifically developed to support the solution of a non-structured management problem for improved decision-making. It uses data, provides easy user interface, and can incorporate the decision maker's own insights. An IDSS may use models, is built by an interactive process, supports all phases of decision-making, and may include a knowledge component (Afraim and Jaye, 1995). The IDSS bring together human judgment and computerized information providing support to decision makers primarily in the analysis of poorly or unstructured situations. The decision makers can either be an individual or a group, a useful capability to address multi-disciplinary problems.

Decision-making in general can be improved if one or more of these procedures can be simplified or automated (Parsons and Jennings, 1998; Panzarasa et al., 2001). It may be possible to extend the capabilities of an IDSS through integration with an expert system to achieve such simplification. In effect, the expert system would be acting in an advisory capacity during several of the decision-making procedures in much the same way as a supervisor. Since the decision maker must define the problem, the variables and the decision model to solve the problem, an intelligent system could be called upon to offer suggestions for various alternatives to be considered, as well as justification for the suggestion. The IDSS gives full control to the user regarding information acquisition, evaluation, and making the final decision. Since the decision process is not completely automated, the user is developing decision-making skills. The main role of an IDSS in an organization is to enable knowledge processing with communication capabilities.

An IDSS can help in the decision-making process for several decisions that a municipal and its partners take daily. An IDSS could address low-level (well defined) decisions like the selection of a course of action among a limited number of alternatives. An IDSS can also tackle medium-level and high-level decisions that imply the synthesis of a large amount of information, and the search for trade-offs between the level of service to the population and the global cost of the system. In urban infrastructures and related services management, these decisions are typically based on an advanced technological and engineering expertise, on knowledge of the needs and demands of the population, on an understanding of the interactions between local, regional and even national policy making, as well as on the interactions between the private and the public sectors.

The IDSS provides information to help the user of a component of the SIGIU decide on a course of action. It may either suggest a decision that the user has to confirm or a set of possible actions for the user to complete the selection. This approach has been used for similar problems (Becker, 1993; Burstein, 1995; Pomerol et al., 1996).

The IDSS used in this paper is based on case-based reasoning (CBR). Case-based reasoning, broadly construed, is the process of solving new problems based on the solutions of similar past problems (Kolodner, 1992, 1993; Levine and Pomerol, 1989). It has been formalized as a four-step process (Aamodt and Plaza, 1994):

- *Retrieve*: Given a target problem, retrieve from memory cases that are relevant to solving it;
- *Reuse*: Map the solution from the previous case to the target problem;
- *Revise*: Having mapped the previous solution to the target situation, test the new solution in the real world (or a simulation) and, if necessary, revise the case;
- *Retain*: After the solution has been successfully adapted to the target problem, store the resulting experience as a new case in memory.

At first glance, CBR may seem similar to the rule-induction algorithms of machine learning. Like a rule-induction algorithm, CBR starts with a set of cases or training examples; it forms generalizations of these examples, by identifying commonalities between a retrieved case and the target problem. Fig. 1 shows the CBR's architecture.

This paper presents a prototype of an intelligent decision support system dedicated to coordinated management of urban infrastructures. It is organized as follows. Section 2 gives some details on SIGIU architecture. Section 3 explicitly describes the IDSS. Section 4 presents the implementation details of the system, and finally, Section 5 presents the conclusion.

2. The architecture of urban infrastructure systems

System integration, reusability and generic systems are the key elements in the success of this type

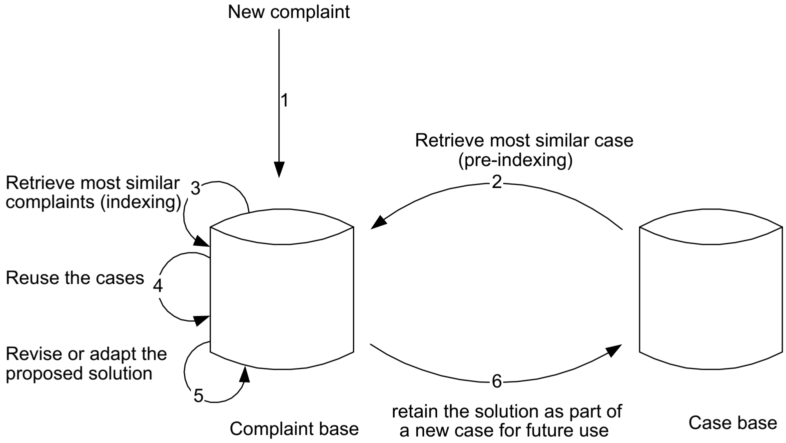

Fig. 1. CBR's architecture.

of application. Unfortunately, the interpretation of those concepts is incorrect and generally results in repetitive, dispersed and thus, non-reusable developments. A municipality alone, cannot design a complete application dedicated to the operation of an urban infrastructure. Municipalities are obliged to use many other developments (proprietary software such as database applications, GIS, DSS, etc.) and try to integrate all in a good manner with their current management system, which is almost never completely computerized. In respect to operation tasks, this results in data duplication and inconsistency. If we design urban systems application, it should take into account reusability for future developments of other urban systems management (Leclerc et al., 2001a).

2.1. The conceptual model of urban infrastructure management

The project and implementation functions are intertwined in the definition and execution of any project, program or activity undertaken in the municipal organization. The analysis of any activity from a multi-disciplinary project to the treatment of a simple and well defined request or complaint reveals clearly that the project function is dominant when the solution is progressively defined often requiring very specialized expertise. The planning and detailed design of a component of an urban infrastructure cannot be completed without the input from experts from the technological and other fields involved. This is also the case for the definition of a preventive maintenance program, the selection of construction methods or the identification of the resources to allocate to the delivery of particular municipal services to the population. Thus in defining the solution and the resources to carry it, expertise relevant to a particular infrastructure or system is essential (Leclerc et al., 2001a,b).

2.2. Municipalities management

Municipalities are in constant search for data, information and knowledge of all kinds coming from various sources and are using them to determine and predict the behavior of their infrastructures at any moment. They tend to have decisional support systems rather than operational systems. Moreover, these decision support systems do not use information from all their urban systems, thus limiting a coordinated management. Good management implies good operation that, in turn, implies to know minimally each characteristic of all urban systems. So the municipalities need to know the structural properties of their urban systems from 'closed circuit television', from ground measurements, and from complaints. They also need to know the dynamic properties (flow, load) of these infrastructures starting from electronics equipments (Konaré et al., 2001).

The task of operations remains delicate because of the abundant quantity of data, which are not necessarily compatible (i.e., of the same format). In fact, the design of robust and evolutionary information systems requires a thorough analysis and must rest on solid conceptual bases (Brazier et al., 2000a,b).

A classification, adapted from (Chocat, 1981; Leclerc et al., 2001a) of the data that a municipal organization and its partners used, defines five generic types:

1. The structural data describe the physical characteristics of the components, their geometry and location.
2. The behavioral data describe the operating characteristics of a component.
3. The thematic data present information derived from a combination of data.
4. The project or program data give information on the human resources, the equipment available, the operating cost, etc.
5. The temporal data provide information on the dynamics of a process or a system.

The data used by an urban engineer or manager can be grouped into one of these generic types. The most widely shared data are the structural data particularly for relative location purposes.

2.3. The SIGIU architecture

The cooperative system on which SIGIU is based is composed of a set of integrated operating systems (SYDEX) and the global planning and coordination system (SYGEC) as shown in Fig. 2. The objective is to integrate the set of SYDEX and the SYGEC into a single coherent system for all of the SIGIU's users according to their tasks, their roles, and their responsibilities within the municipal administration. SIGIU is provided by different measurement and monitoring instruments installed on some system's elements to be supervised. Each of the urban systems considered is managed by a specific SYDEX. Below we list some of the urban systems that have been considered: Sewerage System, Waterworks System, and Energy Management. The use of SIGIU for the effective urban infrastructure management is the fruit of the collaboration of various SYDEX and their individual contributions, that allow a more global view of the activities related to the planning, programming, operation, execution and supervision of jobs.

2.4. The SYDEX architecture

The component within the SIGIU dedicated to the operation of a particular urban infrastructure and of the services this infrastructure supports is the SYDEX. Each SYDEX is concerned by the operation of a particular urban system, addressing questions of its integrated management from the daily operation and preventive maintenance activities to those monitoring its performance and selecting alternatives to improve its response to evolving demands (Konaré et al., 2001). All structures that have been studied have common features that merit to be grouped into a representative system, which is a generic system. To maximize reusability between SYDEX, a generic SYDEX was initially developed as all urban systems that have been studied, have common features that were grouped into a representative generic system (Brazier et al., 2000b; Konaré et al., 2001).

2.5. SIGIU multi-agent system

To specify a multi-agent system as precisely as possible, it is necessary to define the agents' internal knowledge and their behavior, in addition to the way they interact with other agents. The communication between agents must be given a specific semantics. Considering all these aspects, the SYGEC, the SYDEX, the IDSS, MAS can model the knowledge representation, the processes and mechanisms that are part of a consensual knowledge-based system.

The SIGIU can be seen as being composed of four elements:

- A group of agents: IDSS agents, communication agents, and so on. Each agent has some charac-

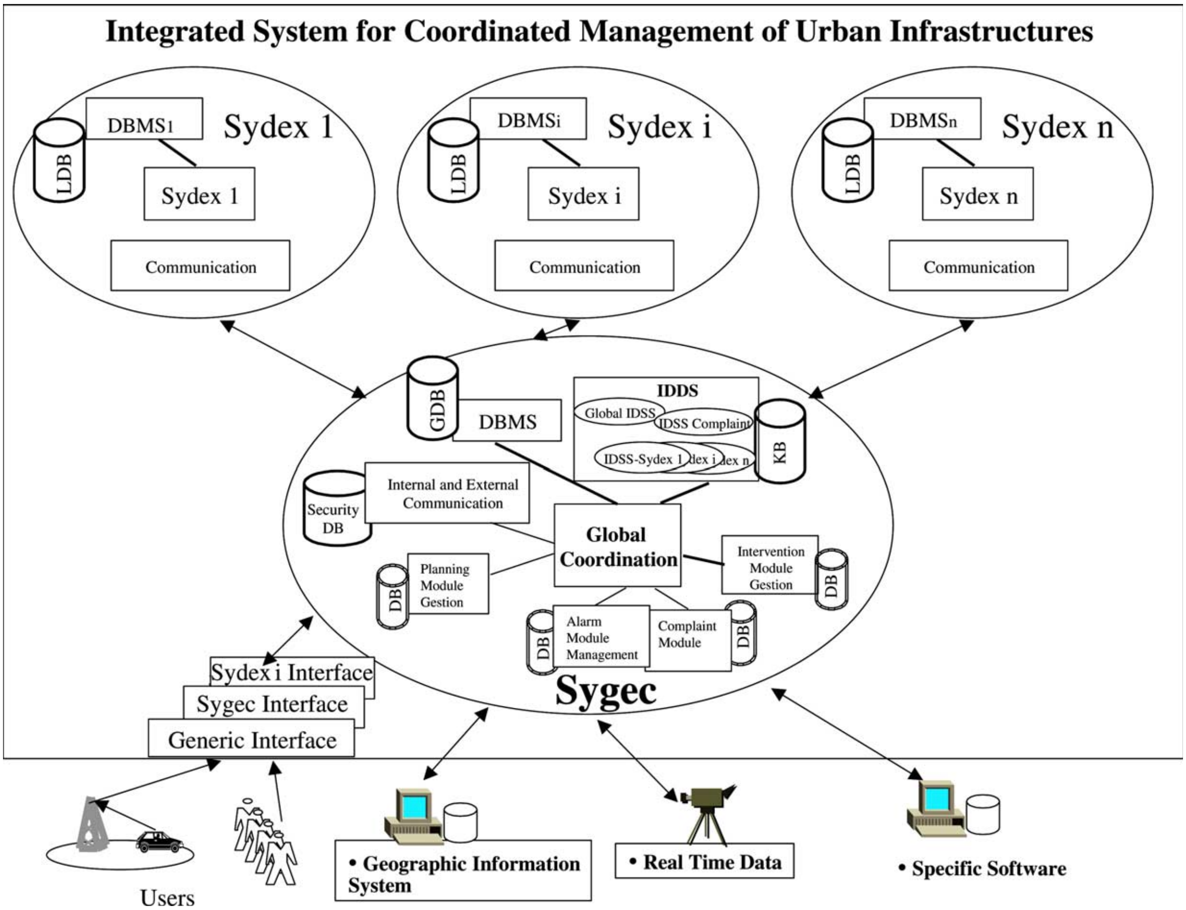

Fig. 2. SIGIU architecture.

teristics (Wooldridge and Jennings, 1995): autonomy, social ability, pro-activeness and reactiveness.
- A group of mobile agents: These are useful for applications that are required to respond in real time to changes in their environment, like alarm management in urban infrastructures, as they can be dispatched from a central controller to directly and remotely carry out operations at the point of interest.
- A set of tasks to be carried out.
- A set of resources: the urban infrastructures and all information associated with them.

In our system, the agents are homogeneous as to their architecture, their operation, control specification, functionality, global goals, knowledge-level communication and ontology.

In systems involving multiple agents, systems builders have traditionally analyzed the task domain of interest and, based on their analyses, imposed upon the agents certain rules that constrain the agents into interacting and communication according to patterns that the designer deems desirable (Gmytrasiewicz and Durfee, 2000). Coordination is a process in which agents engage in order to ensure a community of individual agents act in a coherent manner. Coherence means that the agents' actions gel well, and that they do not conflict with one another (Nwana et al., 1996).

The *control* of an agent is made up of the specification of the goals, the intentions, the plans, and the strategies. To reach these goals, the agents require cooperative working (Ephrati and Rosenschein, 1993).

The *knowledge-level communication* uses conventions at three levels: representation language format, agent communication protocol and specification of the content of shared knowledge.

Finally, *mobile* agents have many characteristics that enable them to enhance managing control and alarms in urban infrastructures: overcoming network latency, reducing network load, executing asynchronously and autonomously, adapting dynamically, operating in heterogeneous environments, and having robust and fault-tolerant behavior (Lange and Oshima, 1998, 1999). Mobility is obviously one of the most important capabilities, and we can certainly benefit from it. However, other agent capabilities also lend themselves for coordinated management of urban infrastructures.

2.6. Coordination, planning and communication in the SIGIU

SIGIU, seen as a whole, exhibits particular characteristics that are described below: cooperation, coordination, control and communication. There are several reasons why multiple agents need to be coordinated (Jennings, 1990): Meeting global constraints, preventing anarchy; distributed expertise, resources or information; dependencies between agents' actions and efficiency.

Coordination among a group of SYDEX allows them to take into account all tasks that are to be completed in order to coordinate their execution: to know and predict at a higher level the behavior of other SYDEX in the system: this is the concrete task carried out by the planning and control at top level; share intermediate results that lead to progress in the solution of the global task, as when the problem involves more than one SYDEX. For example, developing a new neighbourhood for which all urban infrastructures must be built; and avoid redundant actions, when these are not warranted. Coordination can be classified in the following four broad categories (Nwana et al., 1996): organizational structuring; contracting; multi-agent planning and negotiation. The coordination approach used in our system is contracting (Davis and Smith, 1983). In this approach, which assumes a decentralized market structure, agents can assume two roles (Nwana et al., 1996):

- A manager who breaks a problem into subproblems and searches for contractors to complete them, as well as to monitor the problem's overall solution.
- A contractor who does a subtask.

Cooperation takes place at two levels: local tasks and global tasks. Local tasks are those related to each SYDEX's individual interests; global tasks are those that relate to the system's global interests. Global tasks are broken down and each subtask is carried out by SYDEX according to its abilities and under the supposition that integrating the solutions of the subtasks will lead to the global solution.

Control is the basic mechanism that supports coordination in SIGIU. Control relates directly to: determine which tasks are more important to carry out at a given time with respect to each SYDEX and SYGEC; determine what context should be used in solving a subtask, and determine which SYDEX are going to participate and how each will participate in such solution; and evaluate whether or not the solution has been achieved or generated. Control may be seen from two points of view: global control and local control. Global control relates to decision-making based on data obtained and consolidated from the global knowledge and global information of the system. Local control relates to decision-making based only on local knowledge and information.

C*ommunication* is implemented with KQML (Finin et al., 1994a,b,c), supported over KIF (Genesereth and Fikes, 1992), which is used to represent the knowledge or the content of the message itself. In SIGIU, a homogeneous ontology is used to allow the communication among all its elements.

Ontology provides a vocabulary for talking about a domain (Gruber, 1993). Ontology is an explicit specification of a conceptualization. In Gruber (1995) we can find the most essential criteria used during the design of SIGIU ontology.

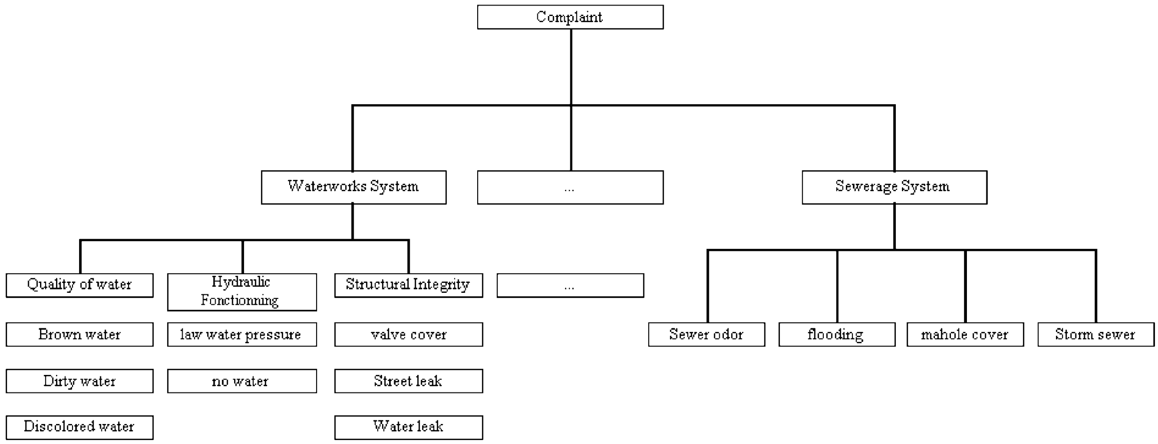

Fig. 3. Intervention task ontology.

These criteria are: clarity, coherence, extendibility, minimal encoding bias and minimal ontological commitment. Within the domain of multi-agent system, there is also a need to design models in which knowledge is context-independent, well defined and structured with the purpose of having sharable and reusable components (Gruber, 1995). During the ontology design of the SIGIU, we have based our design process on the principles discussed above. In our model, we have developed three ontologies: the complaint ontology, the location ontology, and the intervention ontology. Fig. 3 presents the intervention ontology. The aim is to create a structure that can be used in order to define and declare any kind of intervention (task) in the urban infrastructure.

Example 1 illustrates, a communication between the user agent and the complaint agent ("A citizen complains about quality of water") in KIF sentence.

Example 1

KIF sentence

```
(exists ((citizen ?x1) (complaint ?x2))
   (and (expr ?x1 ?x2)
      (theme ?x2
         (exist (Water-Works-System ?x3)
            (theme ?x3
         (exist (quality ?x4)
            (and (= 'bad' ?x4))))))))
```

3. The IDSS

As we have seen in Section 2, UI management is a complex task. The use of computer technologies is essential to the success of its management. In the architecture of the SIGIU, we've introduced decision support system with knowledge bases to improve some common problem solving where knowledge is involved such as how, where and when to make an intervention, how to find the cause of a problem or how to classify knowledge. In this section we are going to talk about the IDSS in general rather its implementation using CBR. We will present the decision process inside the SIGIU, interactions between modules, conflicts about decisions, etc. Finally, we will discuss how CBR is implemented, how knowledge is defined, stored, retrieved, and managed for improving urban infrastructure management.

3.1. IDSS definition

The IDSS provides support to several interdependent and/or sequential decisions, are adaptive over time and flexible, so users can add, delete, combine, change, or rearrange basic elements. The IDSS attempt to improve the effectiveness of decision-making. A *problem solving* process preceded by a *problem finding* process represents decision-making.

Problem finding consists of the identification and formulation of the problem to be solved. Often overlooked or too rapidly completed, problem finding is the key to effective decision-making because a seemingly good solution to the wrong problem is not relevant.

Problem solving is the process of using information, knowledge and intuition to solve the problem previously defined. A common subdivision of the decision-making processes is made into four steps: intelligence, design, choice, and implementation. *Intelligence* includes the collection and analysis of data related to the problem. Key challenges in this phase consist of obtaining complete and accurate data and figuring out what they imply for the decision to be understood. *Design* includes the generation, development and analysis of different decision-making models adapted to the problem and its characteristics. *Choice* consists of the choice between several solutions built in the design phase, which also includes the identification, evaluation and recommendation of an approach to adapt the solution to a dynamic decision-making environment. *Implementation* consists of the decision to apply the solution to the problem identified.

An intelligent decision support system can help in the decision-making process for several decisions that a municipal and its partners take daily. An IDSS can address low-level (well defined) decisions such as the selection of a course of action among a limited number of alternatives. Examples of such decisions are the routing of a request to the proper department or the choice of a remedial action accompanied by the emission of its work order. IDSS can be implemented as a rule-based system, a model-based system or a case-based system. In our case, it is based on case-based reasoning (CBR). The IDSS is composed of a case base that represents expert's knowledge on past problems, situations, actions and solutions (that are good or bad), and a mechanism to manage that knowledge such as the knowledge retrieval, presentation and storage. The good thing with CBR is that in the implementation stage, we can separate the case base with the management mechanism in such a way that the management mechanism can be applied to other case base. We will see later the necessity to introduce generality in the design of the case base inside each SYDEX.

3.2. Decision process inside the SIGIU

The questions in this part are what is a decision, what kind of decisions are made in the case of urban infrastructure management? Then how the decision process is handled. But first, we have to understand the domain. Fig. 4 shows the domain knowledge representation. The rectangle represents items of interest while arcs are relationship between those items. For knowledge discovery, inference mechanisms can use the arcs to find related item of interest (Hederman, 2002). Basically we have citizens who make complaints on infrastructures, and employees who manage those complaints. A complaint has indicators and is related to element of infrastructure, which in turn is related to an urban infrastructure. Departments such as Department of Public Works, Department of Waterworks Systems, etc manage urban infrastructures. Citizens, complaints and infrastructure elements all have a distinct location.

Infrastructure elements have electronic equipments that can generate alarms. For example, we have developed a video application prototype that transmits images from a pumping station to SIGIU and then detects the level of water. Depending of this level, actions are taken. Actions are also generated by complaints. The whole process of decision-making is seen from the complaints point of view. It could have been seen from the alarms point of view.

The Complaint Management Module (CMM) inside the SIGIU makes the complaint management process. It presents the sequential and parallel procedures to determine the immediate action to a new complaint received by the Department of Publics Works. Each time a complaint is received, it follows steps before it can be resolved. Those steps can be disaggregated in seven major categories where many people and many software components intervene such as databases, knowledge bases, rule-based systems, model-based systems and case base systems.

Complaint reception: This part defines the problem finding of the decision-making process.

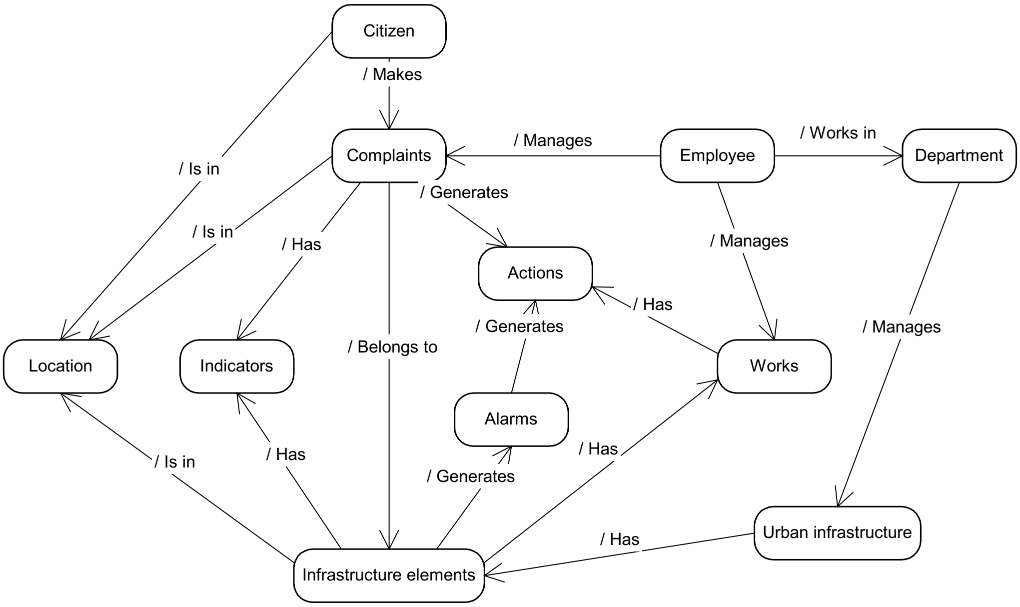

Fig. 4. Semantic net of SIGIU knowledge.

Indeed, it consists of the identification and formulation of the problem to be solved. Problem solving does not start until all required information has been collected. Or, the citizen can fill out a form (on the web, by mail, by fax, etc.) and it will be filed in the system. Fig. 5 shows a form for the problem finding part. Once this is done, the DSS is in the problem solving phase: analysis and routing, solution proposal, solution choice and intervention planning and execution are next.

Complaint analysis and routing: After the complaint reception unit has filed the complaint, CMM starts various analyses. The first one is conducted to check if this new complaint relates to a new event or to an event already identified by previously filed complaints. This part is very important because we do not want to increase the number of complaints resolution. So from the start we have to search for similarity (done by cross-referencing service calls, by searching for duplication of addresses, areas, problems, etc.) between new complaints and others already in the database. This will minimize duplication of actions in the systems. If it is a new complaint, the DSS will start the classification process. If the problem is not well described, a communication process with the user who complains will start (by phone, mail, web or any other process) to correctly define the problem or classify it in the right categories. If well defined, a second analysis is performed to assign a priority to it based on its social and health impacts, public health being a top priority. In a third analysis, the CMM classifies the complaint as a simple complaint, a transgression of municipality rules and laws or a claim for compensation. This initial classification is needed to dispatch the complaint to the department most likely to take care of it.

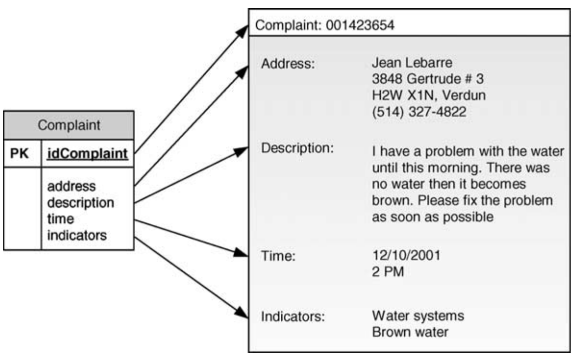

Fig. 5. Complaint representation.

Concurrently, another analysis is completed, based on keywords, to associate the complaint to an urban system or infrastructure.

Complaint technical solution proposal: It is the responsibility of the technical departments to propose the most appropriate action(s) to complaints it received. The SYDEX acts in support of the technical staff to identify potential alternatives, to assess their respective impacts and to select one of them indicating the resources—human, equipment and money—needed to execute the action(s). The action may be to gather additional information before deciding on the appropriate remedial action; it may be to select a remedial action among several alternatives. It may be an action to notify the population in the case of a public health threat. It may also be a combination of the above. For instance, a complaint indicating that the water at the faucet is brown would be sent to the Department of Public Works (DPW) for an immediate action where the opening of close-by fire hydrant to wash-out the colored water, with a report to the Water Distribution Department for further analysis and possibly water sampling for water quality analysis (Ochoa et al., 2001). The problem–action format lends itself to decision based on past experience of the DPW with similar problems with the possibility of adapting the past solution to the new situation, which is different in some ways but similar in many characteristics with those solved in the past. This characteristic is typical of the IDSS developed based on the case-based reasoning (CBR) approach (Watson, 1997).

Complaint solution choice: After a set of possible solutions has been found, the DSS has to present the results to the Manager. He has to select one solution that has some actions coming from the inference mechanism. This step as the precedent is highly interactive between the user and the DSS. The presentation of knowledge from the urban infrastructure, and how to manipulate it (adapting the old solution in different way) is very important.

Intervention planning and execution: It is a coordination task consisting of weighting the priority and compiling the resources required to execute a recommended action considering all other actions to be completed by the municipal organization.

File closure: After all the tasks proposed by the system have been executed, the file can be closed. It might happen that after an intervention, the file is not closed because it leads to another problem.

All those global steps are interdependent and sequential and they can be cyclic. Some of them need the help of a DSS. We know that the DSS with inference mechanisms will guide the decision maker to take a good decision, perhaps not the best, but at least a good one. But first, we have to define what are the decisions from the point of view of urban infrastructures, what kind of decisions can be made in the different steps seen above? The decision process is defined in Fig. 6.

For example, the municipality receives a complaint about a tree. The complainant defines:

- what is the problem? the tree is going to fall;
- where is the problem? in front of the Metro Verdun;
- when did it happen? Tuesday 4 May 2002;
- who called? Miss Appletown;
- how did it happen? don't know.

A complete decision should respond to the following questions:

- what to do? Cut the tree;
- where to send the team? 3255 Gertrude rd.;
- when to send the team? Wednesday 5 May 2002;
- who is involved? Parks and Garden team;
- how to do it? Secure the area first and cut the tree starting from the top.

A decision is the solution seen as a set of actions to a problem (recurring or not). The problem

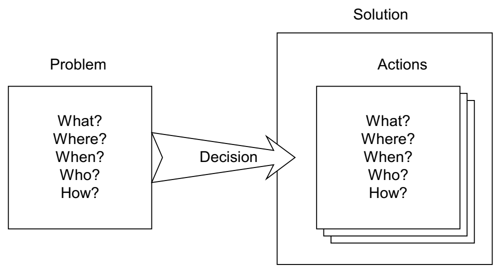

Fig. 6. Problem solution inside the SIGIU.

could come from event sources. We consider event sources as citizens, electronic equipment and also internal processes. Two types of decision exist: simple decisions and complex decisions. Simple decisions like the one described above have little risks and require little knowledge. Complex decisions are the ones that have high risks and lots of knowledge is required. Generally, a complex decision would aim to reach many goals, and that is why knowledge from all related domain to the goals is required. As an example, the decision to rebuild a road is a complex one, because it requires knowledge from other SYDEX's (specially from sewer and waterworks). This is required because so many times people do not consult other departmental knowledge base to synchronize the work and sometimes we see duplication of works by the DPW.

Each decision is important for the system or the person who made the decision. But how is conflict managed when you have limited resources (people and time) and many distributed IDSS? In the previous section, we said that each SYDEX is autonomous and is able to take decisions related to its area of expertise. He does this by giving priorities to all actions. Priorities are defined for infrastructures elements. When SYDEX defines actions, it gives them priorities, based on many criteria such as time of intervention, urban infrastructure indicators, the number of complaints received at the same time, at the same location with the same indicators. Priorities can be expressed with the following formula:

$$P_{\mathrm{D}} = \sum_{i=1}^{N} \alpha_i p_i$$

where P_{D} is the global priority of a decision by a SYDEX or the SYGEC, α_i is the criterion factor and p_i is the priority of the criterion. If two SYDEX come with decisions with same priorities, it has to assign to them different teams, so there is not interference.

After defining the decision processes inside the SIGIU, we are going to show how CBR is implemented to help improve the decision-making process by providing accurate solutions and quicker response time to problems.

3.3. CBR implementation details

Because we are using CBR as the engine to take decision (the DSS implementation), we will have to decide whether a complaint is a new case or is already an equivalent case in the case base. We will discuss how complaints and cases are represented, how storing, indexing, retrieving and adapting occurs. First of all each complaint cannot be a case. That would be a huge limitation of the CBR if it were so, especially for performance limitations. Each time a complaint arrives, it has to be classified so that we can compare it to cases in the case base. For that we need to match the complaint's characteristics to a complaint's ontology, so that all the different stakeholders know what they are talking about. The complaints ontology has been developed and is shown in Fig. 2. The aim is to create a structure that can be used in order to define and declare any kind of intervention on an urban infrastructure.

Once classified, the DSS has to decide whether a new complaint based on some criteria is already in the case-based system. But first we have to see how a case is represented and how the 4R rules are applied here. A complaint as shown in Fig. 3 is represented by its description, its physical (address) and temporal location. The process of grouping complaints by category is called indexation. For that we have to choose from all the information we have analyzed which one of them can characterizes classes of complaint. In memory indicators index cases, and they can be indexed by date time, by geographic location or by any other attributes that a use decides to choose. The user should be aware that dynamic indexation is time and resource consuming because of the so many categories that can be created and can become unmanageable. Those indicators represent something, they are the knowledge of the experts of the systems, and the experts know what they represent, how to deal with them, who can deal with them, and when it occurs. The experts know that flooding cannot appear in winter. Cases are represented hierarchically in memory based on their indicators. A case has a subcase or a parent case as shown on Fig. 7.

While going down to the leafs, cases have more attributes than their parent case. Each case has one

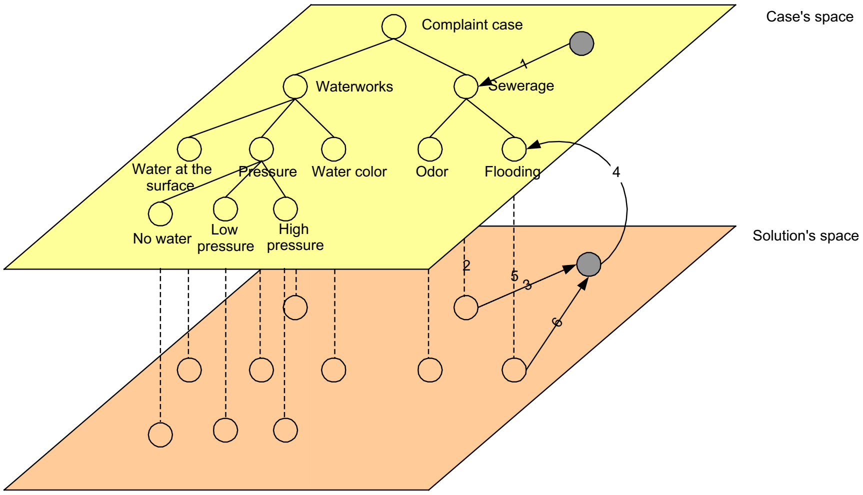

Fig. 7. Cases hierarchy of complaint and solution.

and only one solution. For example, we can have a mother case that is pressure of water relative to the waterworks system. The mother case will have one solution represented by one or more actions such as make an inspection or call the citizen to tell him that there is ongoing work on the system for two days. After the days have passed or the inspection is done, the solution can either be finished or the case mutation can occur. The case will become either low pressure or high pressure and each of the case has a list of actions to be conducted for the case to be solved. Another example is that if we have a complaint where the citizen selects water's color as an indicator, the DSS would retrieve the case inside the database and match the two. The case solution suggests making an inspection. After making the inspection for water sampling, we find that the color is brown and it is very dangerous to the population, we have a new case that is "brown water color dangerous for the population", and that requires other actions than simply washing out some conduits. First after a complaint is received, search is done in the case base to retrieve most similar cases based on similarity measures that will be presented later. For a child case to be retrieved, more information about the complaint will be needed. For example for the first pick "colored water and its solution" will be retrieved by the IDSS as the mother case. Then in the complaints database, all cases with the same indicators and the same mother case will be retrieved. The user will have the choice to adapt one of them and the solution will be applied, intervention and planning will be done. If after the intervention, the problem is not solved, with the new information we have, the IDSS will retrieve the child's solutions. This will help define where to send the complaint. Then similar complaints will be retrieved from the complaints database to see whether two or more complaints should be treated the same way. For example if 10 people call for a broken light in the street, it is essential that each call following the first one should be considered as one complaint that needs one and only one solution and perhaps many responses to all the complainants. Once a similar case has been retrieved, different types of adaptation are proposed to the user. The process is not automatic, but interactive. For example the IDSS proposes to replace all-important fields, and changes the date and location, or he can suggest a list of choice for each attributes of the new complaint's solution. This list comes from the many cases that come from complaint case.

All those complaints solutions have been adapted from one case base. After the complaint adaptation, we have the choice to save the complaint as a new case in the case base. This process is not automatically done, but rather, it is proposed in an interactive fashion to the case base administrator (an expert). The case is saved with respect to the infrastructure's indicators in the case base. In the case base we do not have time or location, but just solutions.

Case retrieval: case retrieval is an important issue in CBR. It is essentially based on similarity algorithms such as nearest-neighbour and inductive retrieval. The two approaches are used here. For new complaints regrouping so that we do not want 10 solutions and actions for the same problem, we have to identify if two or more complaints are similar. Two and more complaints are similar if geographical proximity, temporal proximity and content proximity are verified. Complaints are in the same area if the distance that separate them is below a threshold:

$$\mathrm{sim}(c1, c2) = |d1 - d2| < \varepsilon_d$$

where d_i represents the relative position of complaint c_i.

Complaints are time related if they came under the same time period:

$$\mathrm{sim}(c_1, c_2) = |t_1 - t_2| < \varepsilon_t$$

where ε_t represent a time value that depends on the type of problem. If it is water contamination, then ε_t will relatively be smaller than if it was a lighting problem.

Complaints are similar in contents if they have the same indicators, or almost the same description.

Based on those three local similarities for a complaint, the IDSS can suggest that two or more complaints are related and should be treated the same way.

Inductive retrieval is used to retrieve cases and solutions from the case base. As the case base is organized hierarchically, depending on the features of a complaint, the IDSS will follow the tree to retrieve solutions. The algorithms go from the top of the tree to the leafs by asking questions and selecting the cases that best respond to the questions. This process is quick if the case base is not huge.

Adaptation: Case adaptation occurs after similar cases have been retrieved. It involves substituting attributes of the new case's solution by attributes of a retrieved case among the list of retrieved case. Basically two types of adaptation are used here: simple adaptation and complex adaptation. Simple adaptation is the substitution of a complaint's solution by a case solution, it is almost automatic and the user has the choice to accept, modify or reject the solution. This style of adaptation occurs for simple common repetitive problems like tree complaints, which do not involve many infrastructures. Complex adaptation is an iterative and interactive process. Because the retrieval process has retrieved few cases that have nothing in common, the IDSS has difficulty to choose one solution. For each attributes of the new complaint, the IDSS searches for the best suitable values; for example, a complainant that selects water's odor, this is related to waterworks, sewer elements or works that were previously done. With the help of the semantic network and the complaints general ontology, the IDSS will look for works that were done few days ago, he will search for elements of infrastructure near the complaint location area and he will propose a series of actions depending of the result found. Complex adaptation generally occurs for complex problem.

4. Management improvement, implementation and results

A prototype of the CMM has been designed. It helps understand the decision process inside the SIGIU with complaints at the starting point. It could have been presented with alarms or others stimulus coming from the inside (recurrent events inside the municipality area of decision) or the outside (recurrent event outside the municipality area of decision). First we will present some of the interfaces of the CMM that have been tested, and then we will define the level of improvement that a system like SIGIU brings. Fig. 8 shows a new complaint that was received by a virtual clerk and forwarded to the right department. This new complaint is saved in the complaint base and is consider an incomplete case because the DSS has not found a solution for it yet. But, based on

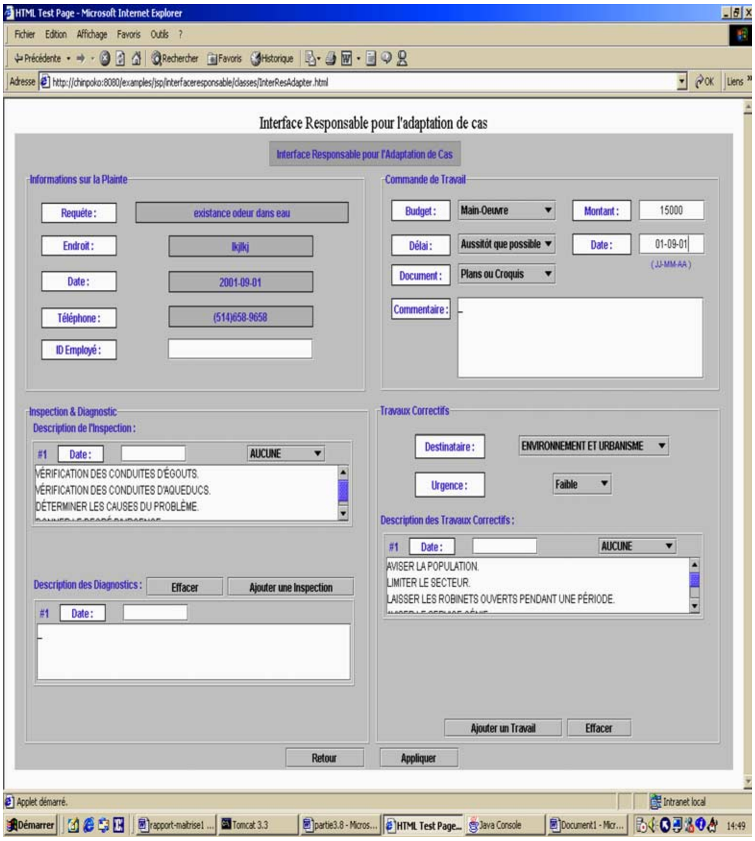

Fig. 8. Case adaptation.

indicators, the IDSS proposes a similar case's solution from the expert case base. Once the solution is applied, and the file is closed it will become a case from the adapted case base.

The indicator is water odor and a series of immediate actions is recommended for such inspections as verifying network elements in the nearest neighbourhood to find a problem. And at the same time, some other actions have to be executed such as open the faucet for a long period of time. Many other interfaces has been developed to manage cases in the expert's case base and in the adapted case base.

The question here is where is the improvement? Improvement level has quantitative and qualitative aspects. What interests us is the qualitative aspects because it is not necessary to compare response time of the implemented system, or time to close a file or to respond to a complaint when decisions that are proposed are not implemented. We think that the best measurement of the improvement level is by measuring its precision. Moreover quantitative measures depend on the size of the case base, the database, and the machine that have been used. Getting measures of improvement of the whole SIGIU required a living laboratory like the city of Martigny in Switzerland. Basically only the CMM interfaces, automation process and some reliability and precision measures of the DSS have been tested at the city of Verdun in Canada. The improvements that have been done are:

- Knowledge sharing: By using open technology on the Internet, the sharing of data, information and knowledge become easier than ever. Security features are not the purpose here but a particular attention has been identified on this aspect. There are many decision levels to take a decision and a person represents each. With a tool like SIGIU each actor is aware of what kind of decision are taken with respect to their hierarchy, they are aware of what is going on where and when and who is in charge of what. With that they can take better and better decisions every day.

- Increasing the level of automation: With the IDSS implemented, the level of automation has been improved a lot. It takes a maximum of two days to redirect a complaint to the right departments. The IDSS support the actors in the decision-making process by filling attributes automatically, by looking for other features that the actor did not think of such as "where are the elements of infrastructure involved at this address?". It will find a priority, resources and other information in the whole decision process of urban infrastructure management
- Decreasing of redundant complaints: Without the help of the IDSS, it was pretty hard to find that two complaints that have been filled have the same concern. For example, 10 people can call for a broken light in the street. In fact with the retrieval process of CBR, similarity measures are applied to each new complaint. In that way the DSS is able to identify two similar complaints and decide that they should have one common treatment even if they have different complainant
- Precision of decision-making: with the introduction of two bases, the DSS is able to find out experts' original case and adapt them. Instead of having only one case base organized in flat fashion, we have two case bases organized in a hierarchical fashion. The research process of similar cases is first done in the expert's case base as a pre-indexing mechanism. That base should not have thousands of cases. The actors have the choice to adapt this original expert's case or to adapt an already adapted case in the adapted case base.

Each year, around one thousand complaints are filed and all of them are processed manually, therefore, the response time varies from a day to months, so does the complaints' resolution time. Some of them simply remain unsolved or lost.

We decided to test the decision support system with complaints coming from the City of Verdun. Complaints from the whole month of May 1996 have been input into the system. This month is similar to other months in terms of the type of complaints filed. Depending on the months, the number of complaints varies from 16 in December to 108 in May in the year 1996, with a mean value of around 70 complaints a month for that year.

Fig. 9 represents temporal and spatial distribution of complaints. The number beside the symbol represents the day the complaint was filed in, either by a phone call, at the desk, by fax or by e-mail. For that month, around 100 complaints have been filed. In order to avoid overloading the map, only 51 of them are represented. Star symbols represent lighting complaints (18) while circle symbols represent embellishment complaints (33). We did not represent other types of complaints such as the one regarding waterworks, sewerage, snowing, parks, signalization or road network. Polygons represent similar complaints that can be handled the same way and that can use almost the same case from the case base. Because the timing is not critical as in the event of water contamination, or other types of more important problems, we decided to choose an $\varepsilon_t =$ three days and an $\varepsilon_d = 500$ m. The system found out that out of 18 lighting complaints, 1 similarity (May 22nd), meaning that two different people called in to report the same problem. For embellishment, out of 33 the system founding out three similarities (May 15th, 21st and 24th of May). This proves that the system is able to find similarities out of previously thought unrelated calls. Also, the system is able to find out complaints of the same type, that occur in the same area at the same time. That kind of complaint merging helps diminish the number of intervention. Case retrieval is based on first, the type similarity and then, geographical similarity. When the case has been retrieved it can be automatically be reused or adapted.

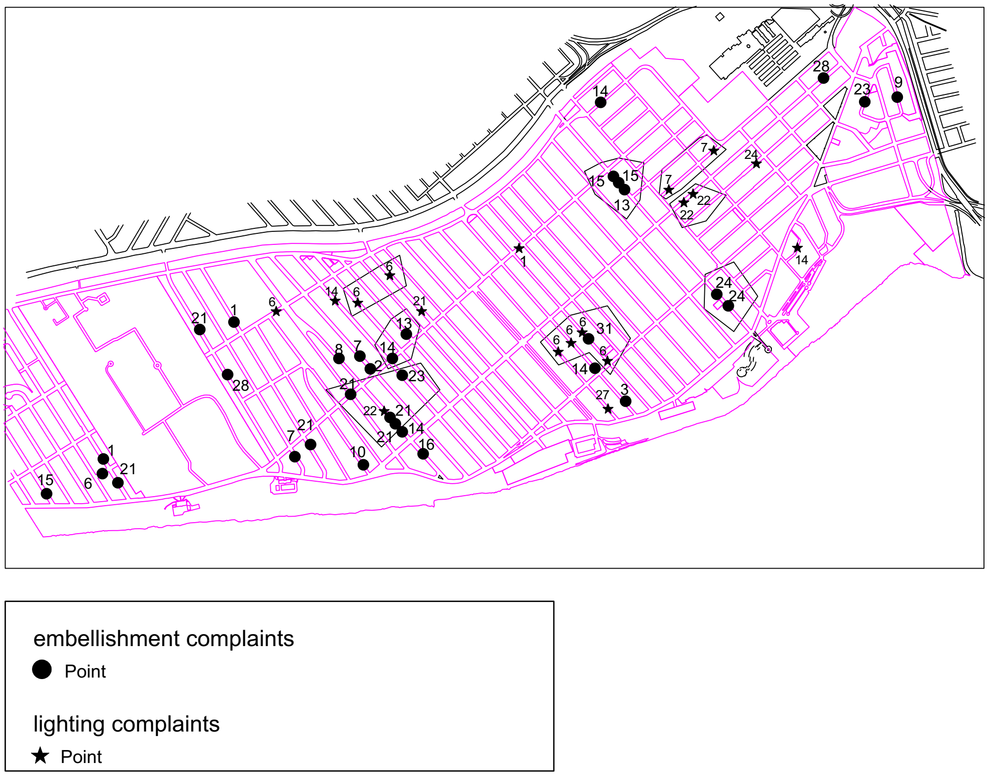

Fig. 9. Temporal and spatial distribution of complaints.

5. Conclusion

In this paper, we proposed a prototype of an intelligent decision support system (IDSS) dedicated to coordinated management of urban infrastructures. This system identifies the data and related treatments common to several municipal activities and defines the requirements and functionalities of the computer tools developed to improve the delivery, performance and coordination of municipal services to the population.This prototype combines decision-making and knowledge-based approaches, mobile agents and multi-agent system technologies. This combination has been used to achieve a generic system. Our focus on the use of generic models, knowledge representation and IDSS is the most distinctive feature.

The SIGIU is dedicated to the management, regulation, interactive and dynamic monitoring of urban infrastructures in an efficient and correct manner. This allows an optimal functioning of some urban systems of a city. In order to support the decision-making process an IDSS was developed as a knowledge-based system provided with inference mechanisms that enables SYGEC and SYDEX to make strategic choices in terms of technical interventions on municipal infrastructures. Intelligent decision support system was used to aid the decision maker in the selection of actions to be taken in urban infrastructure management.

Preliminary implementation results have shown that this specification can lead to an intelligent and generic system, which effectively and efficiently supports decision-making related to managing urban infrastructures.

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