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MANAGEMENT OF INDUSTRIAL WASTEWATER DISCHARGES IN RIVER BASINS THROUGH AGENTS' ARGUMENTATION

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Management of industrial wastewater discharges in river basins through agents' argumentation

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Certifiquen

Que la Llicenciada en Ciències Ambientals Montse Aulinas Masó ha realitzat, sota la seva direcció, el treball que amb el títol **"Management of industrial wastewater discharges in river basins through agents' argumentation"**, es presenta en aquesta memòria la qual constitueix la seva Tesi per optar al Grau de Doctora en Medi Ambient per la Universitat de Girona.

I perquè en prengueu coneixement i tingui els efectes que corresponguin, presentem davant la Universitat de Girona l'esmentada Tesi, signant aquesta certificació a

Girona, juliol de 2009

Manel Poch Espallargas   Ulises Cortés Garcia

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Abstract

Wastewater management is a very complex task. There is a high number of known and an increasing number of unknown pollutants whose individual and collective effects are very difficult to predict. Identifying and evaluating the impacts of environmental problems resulting from the interactions between our social system and its natural environment is a multifaceted critical issue. Environmental managers require tools to support their diagnoses for solving these problems.

The contributions of this research work are twofold: first, to propose the use of an agent-based modelling approach in order to conceptualize and integrate all elements that are directly or indirectly involved in wastewater management. Second, to propose a framework based on argumentation that allows to reason effectively. The thesis provide some real examples to show that an agent-based argumentation framework can deal with multiple interests and different agents' perspectives and goals. This help to build a more effective and informed dialog in order to better describe the interaction between agents.

In this document we first describe the context under study, scaling down the global river basins system to the urban wastewater systems and giving some more details for the specific scenario of industrial wastewater discharges. Then, we analyze the system in describing intelligent agents that interact. Finally, we propose some reasoning and deliberation prototypes by using an argumentation framework founded on non-monotonic logics (*i.e.* permitting to learn things that were previously not known) and the *answer set programming* specification language (*i.e.* a declarative programming language).

It is important to remark that this thesis links two disciplines: environmental engineering (specifically the area of wastewater management) and computer science (specifically the area of artificial intelligence), contributing to the required multidsciplinarity needed to confront the complexity of the problem under study. From environmental engineering we obtain the domain knowledge whereas the computer science field permits us to structure and specify this knowledge.

Resum

La gestió de l'aigua residual és una tasca complexa. Hi ha moltes substàncies contaminants conegudes però encara moltes per conèixer, i el seu efecte individual o col·lectiu és difícil de predir. La identificació i avaluació dels impactes ambientals resultants de la interacció entre els sistemes naturals i socials és un assumpte multicriteri. Els gestors ambientals necessiten eines de suport pels seus diagnòstics per tal de solucionar problemes ambientals.

Les contribucions d'aquest treball de recerca són dobles: primer, proposar l'ús d'un enfoc basat en la modelització amb agents per tal de conceptualitzar i integrar tots els elements que estan directament o indirectament involucrats en la gestió de l'aigua residual. Segon, proposar un marc basat en l'argumentació amb l'objectiu de permetre als agents raonar efectivament. La tesi conté alguns exemples reals per tal de mostrar com un marc basat amb agents que argumenten pot suportar diferents interessos i diferents perspectives. Conseqüentment, pot ajudar a construir un diàleg més informat i efectiu i per tant descriure millor les interaccions entre els agents.

En aquest document es descriu primer el context estudiat, escalant el problema global de la gestió de la conca fluvial a la gestió del sistema urbà d'aigües residuals, concretament l'escenari dels abocaments industrials. A continuació, s'analitza el sistema mitjanant la descripció d'agents que interaccionen. Finalment, es descriuen alguns prototips capaços de raonar i deliberar, basats en la lògica no monòtona i en un llenguatge declaratiu (*answer set programming*).

És important remarcar que aquesta tesi enllaça dues disciplines: l'enginyeria ambiental (concretament l'àrea de la gestió de les aigües residuals) i les ciències de la computació (concretament l'àrea de la intel·ligència artificial), contribuint així a la multidisciplinarietat requerida per fer front al problema estudiat. L'enginyeria ambiental ens proporciona el coneixement del domini mentre que les ciències de la computació ens permeten estructurar i especificar aquest coneixement.

Resumen

La gestión de las aguas residuales es una tarea compleja. Hay muchas sustancias contaminantes conocidas pero aún muchas por conocer. Su efecto individual o colectivo es difícil de predecir. La identificación y evaluación de los impactos ambientales resultantes de la interacción entre los sistemas naturales y sociales es una tarea multicriterio. Los gestores ambientales requieren de herramientas para hacer sus diagnósticos para solucionar los problemas ambientales.

Las contribuciones de ese trabajo de investigación son dobles: primero, proponer el uso de un enfoque basado en la modelización de agentes para conceptualizar e integrar todos los elementos que estan directa o indirectamente involucrados en la gestión del agua residual. Segundo, proponer un marco basado en la argumentación con el objetivo de permitir razonar efectivamente. La tesis contiene algunos ejemplos reales para mostrar como un marco basado en agentes que argumentan puede soportar la integración de diferentes intereses y perspectivas. Consecuentemente, puede ayudar a construir un diálogo más informado y efectivo y, por lo tanto, describir mejor las interacciones entre los agentes.

En ese documento se describe, primero, el contexto estudiado, escalando el problema global de la gestión de la cuenca fluvial a la gestión del sistema urbano de las aguas residuales, con un enfoque especial a la gestión de los vertidos industriales. A continuación, se analiza el sistema mediante la descripción de agentes que interaccionan. Finalmente, se describen algunos prototipos capaces de razonar y deliberar, basados en la lógica no monótona y en un lenguaje declarativo (*answer set programming*).

Es importante remarcar que esa tesis une dos disciplinas: la ingeniería ambiental (concretamente el área de saneamiento) y las ciencias de la computación (concretamente el área de la inteligencia artificial), contribuyendo así a la mutidisciplinariedad requerida para hacer frente al problema estudiado. La ingeniería ambiental nos proporciona el conocimiento de dominio, mientras que la inteligencia artificial nos permite estructurar y especificar ese conocimiento.

Papers with contribution

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List of acronyms

AA	Administration Agent
ABM	Agent-Based Modelling
ABS	Agent-Based Simulation
ABSS	Agent-Based Social Simulation
AF	Argumentation Framework
AF_P	Possibilistic Argumentation Framework
AIP	Agent Interaction Protocol
AOSE	Agent-Oriented Software Engineering
arg	Argument
AS	Argument Schemes
ASM	Activaded Sludge Model
ASM	Argument Source Manager
ASP	Answer Set Programming
ASR	Argument Source Repository
BAT	Best Available Technique
BDI	Belief-Desire-Intention
BOD	Biochemical Oxygen Demand
ByA	Bypass Agent
ByM	Bypass Management role
CBR	Case Base Reasoning
CHA	Charge Administrator role
COD	Chemical Oxygen Demand
Cond	Conductivity
CQ	Critical Questions
CSO	Combiend Sewer Overflow
CSOM	CSO Monitor role
DAI	Distributed Artificial Intelligence
DCK	Domain Consented Knowledge
DN	Denitrification
DO	Dissolved Oxygen
DSS	Decision Support System
EDMS	Environmental Data Management System
EDSS	Environmental Decision Support System
EPS	Extracellular Polymeric Substance
ESS	Environmental Simulation System
F:M	Food to Microorganisms ratio
FIPA	Foundation for Intelligent Physical Agents
HA	Household Agent
HRT	Hydraulic Residence Time
IA	Industrial Agent
IEDSS	Intelligent Environmental Decision Support System
IPPC	Integrated Pollution Prevention and Control
IRBM	Integrated River Basin Management
ITA	Industrial Tank Agent
IUWS	Integrated Urban Wastewater System
IWTP	Industrial Wastewater Treatment Program
MA	Meteorological Agent
MA	Mediator Agent
MAS	Multi Agent System
MDH	MeteorologicalDataHandler role
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
N	Nitrogen
NN	Nitrification
P	Phosphorous
PSARI	Pla de Sanejament d'Aigües Residuals Industrials
PSARU	Pla de Sanejament d'Aigües Residuals Urbanes
RAS	Recycle Activated Sludge
rbCOD	Readily Biodegradable Chemical Oxygen Demand
RBOM	Readily Biodegradable Organic Matter
RPA	River Protection Agent
RQM	RiverQualityMonitor role
RSS	River Sensitivity Surveillance role
RTC	Real Time Control

LIST OF ACRONYMS

S	Answer Set
SA	Sewer Agent
SRT	Sludge Residence Time
STA	Sewer Tank Agent
SVI	Sludge Volumetric Index
SW	Software
T	Temperature
TKN	Total Kjeldhal Nitrogen
TSS	Total Suspended Solids
Turb	Turbidity
UML	Unified Modelling Language
UWS	Urban Wastewater System
UWTP	Urban Wastewater Treatment Program
WAS	Waste Activated Sludge
WFD	Water Framework Directive
WQO	Water Quality Objective
WTA	Wastewater Treatment Agent
WWCD	Wastewater Collection and Distribution role
WWP	WasteWaterProducer role
WWR	Wastewater Retention role
WWT	WasteWaterTreatment role
WWTP	Wastewater Treatment Plant

Chapter 1

Introduction

1.1 Motivations

Water is an essential natural resource as well as a social and economic good. All human activities need water to take place: quantity and quality determines the nature of its use. However, the inefficiency and/or inadequacy of water management measures, and even sometimes the lack of water management, has lead to water scarcity, its gradual deterioration and aggravated pollution.

Water pollution is intrinsically connected with human activities. Water, apart from being a vital requirement for biotic life and industrial processes, it also works as a transport mechanism and a sink for domestic, agricultural and industrial waste causing pollution. Water pollution caused by human activities threatens human health and the functioning of aquatic ecosystems, thus reducing effective availability and increasing competition for water of adequate quality.

Important developments are being applied in order to deal with water pollution. However, the majority of them center their attention on improving treatment technologies. Hence, approaches are focused on one piece of the overall water complex system instead of perceiving the problem of water pollution as a global basin problem. In fact, river basins are dynamic over space and time, and any single management intervention has implications for the system as a whole. Consequently, an *Integrated River Basin Management* approach appears as the required solution.

According to (146) *Integrated River Basin Management (IRBM) is the process of coordinating conservation, management and development of water, land and related resources across sectors within a given river basin, in order to maximize the economic and social benefits derived from water resources in an equitable manner while preserving and, where necessary, restoring freshwater ecosystems.* The same Global Water

Partnership Technical Advisory Committee propose seven key elements for a successful IRBM initiative. As follows:

- A long-term vision for the river basin, **agreed** to by all the major **stakeholders**.
- **Integration** of policies, decisions and costs across sectoral interests such as industry, agriculture, urban development, navigation, fisheries management and conservation.
- **Strategic decision-making** at the river basin scale, which guides actions at sub-basin or local levels.
- **Effective timing**, taking advantage of opportunities as they arise while working within a strategic framework.
- Active **participation** by all relevant stakeholders in **well-informed** and transparent planning and decision-making.
- Adequate investment by governments, the private sector, and civil society organizations in capacity for **river basin planning** and participation processes.
- A solid foundation of **knowledge** of river basins and the natural and socio-economic forces that influence it.

In this context, wastewater management is a very complex task. There is a high number of known and an increasing number of unknown pollutants whose individual and collective effects are very difficult to predict. Identifying and evaluating the impacts of environmental problems resulting from the interactions between our social system and its natural environment is a multifaceted critical issue. Environmental managers require tools to support the diagnosis and solving of these problems.

Managing wastewater as an important part of the whole water system administration to be efficiently applied in everyday practice needs knowledge. ***Knowledge-based systems*** can play an important role in this context (59). Some of the principal reasons are their ability to deal with:

- the high complexity of environmental problems,
- the multidisciplinary nature of these problems and,
- the 'objective' power of knowledge-based systems in a highly subjective problem solving context.

There is a lack of appropriate scientific approaches to analyse the dynamics of the interactions between social systems and the natural environment in which they are developed (144). The ***agent-based modelling*** approach has been increasingly used in projects concerned with human-environmental management problems. Agent-based modelling might help to understand the complex processes involved in wastewater management, as it enables to represent:

- dependencies and feedbacks between the different actors on several levels, as well as between actors and their environment,
- micro-level processes, such as decision-making processes of individuals,
- heterogeneity within the actors' population,
- diffusion constraints like imperfect information, uncertainties, and limited resources, and
- the relevance of context in time and space in assessing the management options due to non-linearities and interdependencies.

Classical approaches in water management are based on mathematical modelling of hydrological data, mathematical models for optimization and control of reservoirs seen from the hydrological aspects, models of optimized water management in dry periods, models of biological treatment processes, or elementary models of transference and transformation of pollutants in rivers. In case of inaccessibility, incompleteness, or incorrectness of data as well as in other situations with high degree of uncertainty, experts are still able to make decisions, while all these classical approaches fail; neither algorithmic solution nor exact formulæ can be used.

From the area of soft computing, some experiences can be found to overcome the obstacles related to the lack of data when dealing with environmental problems (53; 127; 168). However, these approaches are not always fully satisfying. Here the space for the utilization of the knowledge-based technologies and for knowledge management opens.

Moreover, agent-based approaches introduce a powerful metaphor in the field of Intelligent Environmental Decision Support Systems (IEDSS) as agents integrate a collection of functionalities, achieved by the interplay about certain problem types and about the environment in which those agents operates (59).

Accordingly, our proposal is to introduce an agent-based design approach for the urban wastewater system concerning a catchment scale, in which *agents*[1] can effectively reason and argue to support critical decisions.

1.2 Objectives

Two main starting hypothesis frame our research. As follows,

Hypothesis 1: The improvement of river water quality can be achieved through the construction of a dialog-based Decision Support System (DSS) of the different agents implied in the wastewater management river basin scenario.

Hypothesis 2: An agent-based argumentation framework can tackle with multiple interests and different agent's perspectives and goals, and help to build a more effective and informed dialog in order to better describe the interaction between agents who have to make a satisfactory/acceptable decision over a proposed action or in front of an emergency.

These hypothesis lead to the formulation of the main thesis statement, that is,

Thesis: The use of Agent-Argumentation based component as Decision Support System and as Knowledge Acquisition methodology can improve the state-of-the-art methods of an integrated wastewater management at river basin scale by providing evidential and experiential knowledge to solve problems.

Accordingly the main objective of this thesis consists on

OBJECTIVE: To build a Knowledge-based model enabling agents' argumentation to improve the management of industrial discharges in a river basin, augmenting the reliability of environmental decisions in this context.

1.3 Contribution

Pursuing the main objective of this thesis, that is to build an agent knowledge-based model to support the management of wastewater, the main contributions are focused on conceptualization and design issues. Doing so, we aim to analyze the main components, relations and global organizational behaviour, pointing out the use of agents and

[1] That is, the several software components representing urban wastewater system elements and stakeholders. The notion of intelligent software agents will be introduced in Chapter 4.

multi-agent systems in environmental complex domains, specifically to manage water pollution.

Concretely the main contributions of this work can be summarized as follows:

- A review of agent-based modelling experiences in the field of environmental management, depicting the current state-of-the-art in this area and the appropriateness of agent-based methodologies to be used to manage environmental complex systems.

- A *multi-agent based model* of the urban wastewater system in the context of river basins, describing and representing the relevant components as agents that interact. These agents have roles and tasks to accomplish and patterns of communication between them. All these features are described for a better comprehension of the system itself. The overall model is built by means of three sub-models: an agent model describing roles and agents, an interaction model describing the communication patterns and finally an organizational model, derived from the previous ones.

- An *agent's reasoning* framework, based on a non-monotonic logic reasoning approach. We propose a way to specify the complex and often uncertain knowledge of the system, in order to make it explicit and usable by the agents.

- An *agents' deliberation framework* based on argumentation for supporting decision-making processes. It gives support to the experts participation in the managements tasks, as well as permits to elicit new relevant information.

- A general *discussion* specially aimed to integrate the components of the overall proposal.

1.4 Thesis Overview

This thesis is structured in nine chapters, including the introduction one:

Chapter 1 summarizes the main motivation, objectives and contribution of this thesis.

Chapter 2 presents and outlines the system related knowledge, components, structure and organization, as well as interactions and common problems. It also outlines the current modelling approaches and challenges reported in the literature.

Chapter 3 is a review of agent-based approaches in the field of environmental systems management, giving special emphasis on those systems related to water resources management.

Chapter 4 describes the principal theoretical concepts *w.r.t* agent modelling methodology. This chapter provides the thesis theoretical framework.

Chapter 5 describes in detail the design of the urban wastewater system in the context of river basins; that is, the agents, roles, protocols, services and acquaintances.

Chapter 6 presents an implementation of agent knowledge using a possibilistic declarative approach, able to capture agent's reasoning and some uncertainties of the domain.

Chapter 7 presents an Agent-based argumentation framework to allow deliberation in the river basin multi-agent system. Using the previous specified knowledge and the designed multi-agent system it proposes an argument interaction protocol to permit the deliberation.

Chapter 8 presents a discussion about the possible integration of the agent-based approaches presented in this thesis.

Chapter 9 portrays the general conclusions and outlines some of the future work lines.

Appendix A contains the proposed FIPA protocols, messages and sequential diagram for the river basin multi-agent system.

Appendix B contains a simple program for the 'industrial wastewater discharge case study' (a piece of codification that can be executed).

Chapter 2

Wastewater management in the river basin context

This chapter gives an overview of the principal components and features related to the studied system. We will put special emphasis on the relationships between the different components as well as on the actual management of the system (management policies and criteria) and how the different emerging problems are solved or tackled. The main objective of this overview is to point out the complexity and thus, the challenges, of the integrated management of industrial wastewater discharges in the context of river basins.

2.1 Regulations and pollution-prevention policies

Water quality management policies on a river basin scale are of special importance in order to prevent and/or reduce pollution of several human sources into the environment. Industrial effluents represent a priority issue particulary in urban wastewater systems that receive mixed household and industrial wastewaters, apart from rainfall water. In particular the contribution from industry must be properly regulated in order to avoid operational problems at the Wastewater Treatment Plant (WWTP) and transfer of pollutants in the effluent or sludge (87). Hereby it is presented a summary of the principal possible water quality management strategies (§2.1.1). Then, sections §2.1.2 and §2.1.3 give an outline on the current legislative European framework and how it is regionally adopted.

2.1.1 Water quality management policies

Several management policies are being developed aimed at maintaining or improving water quality on a river basin level. They can be classified according some constraints imposed on the problem *e.g.* minimum treatment level, ambient water quality standards, effluent standards, total emission caps, *etc.*, either individually or in combination, to model various policy alternatives (102). As follows,

- Effluent standard based strategies (*i.e.* emission-based) (191) such as
  - define the effluent concentration on individual pollutants or groups,
  - set an annual total load standard (based on total emission reductions) or,
  - set technological standards based on the Best Available Technology (BAT).
- Ambient water quality objectives strategies (*i.e.* immission-based) (82) based on setting ecosystem-based quality objectives.
- Economic based strategies, based on economic instruments (89). They can work either by changing prices or by limiting the quantity of an environmental resource that may be used (*i.e.* price-based instruments and quantity-based instruments, respectively).

In practice, the combined use of these policy strategies seems to be the best way to manage water quality since it is in line with the related European Community Directives (§2.1.2) with the main focus on *pollution prevention* and *carrying capacity* principles.

2.1.2 European directives for pollution prevention

Several European Directives have a direct or indirect influence on water quality of European rivers (see Figure 2.1). From nineties new directives were introduced to prevent water quality deterioration going beyond the *human health protection* approaches, such as the Directive 91/271/EEC. Some of the other most relevant directives, in line with pollution prevention policies, are the Integrated Pollution Prevention and Control and the Water Framework directives.

Directive 91/271/EEC concerning Urban Wastewater Treatment (40) set clear infrastructure targets of wastewater treatment for all European urban settlements according to different classes of receiving waters sensitivity. The directive state that there should be wastewater collection and treatment for all settlements above 2000

Population Equivalent (PE) with biological treatment, plus nutrients removal where the affected waters show an elevated nitrates level and/or eutrophication.

Directive 96/61/EC on Integrated Pollution Prevention and Control (from now IPPC) (41) was developed to apply an integrated environmental approach to the regulation of certain industrial activities. This means that, at least, emissions to air, water (including discharges to sewer) and land must be considered together. It also means that regulators must set permit conditions so as to achieve a high level of protection for the environment as a whole. These conditions are based on the use of BAT, which balances the costs to the operator against the benefits to the environment. IPPC aims to prevent emissions and waste production or reduce them to acceptable levels by means of permits based on BAT (41; 191).

Water Framework Directive (2000/60/EC)(from now WFD) (43), aims to establish a framework for the protection of water bodies in Europe. It intends to apply to all water bodies, including rivers, estuaries, coastal waters (out to a minimum of one nautical mile), and artificial water bodies (such as docks and channels). The WFD provides for a combined approach of *emission limit values* and *environment quality standards* by setting out an overall objective of good status for all waters as well as supporting source controls. The WFD co-ordinates the application of all European Union water-related legislation (*e.g.* Urban Wastewater Treatment, Nitrates, Integrated Pollution Prevention and Control, Seveso, Habitats Directives, *etc.*; see Figure 2.1) with the aim to provide a coherent management framework, so as to meet the environmental objectives of these instruments and the WFD itself.

Accordingly, its aim is to take a holistic approach to water management by introducing a single system of water management by river basin - the natural geographical and hydrological unit - instead of according to administrative or political boundaries. This supposes a coordinated, supra-national approach to achieve the set of environmental objectives.

2.1.3 Regional legislation

Several national and regional efforts are being done in order to improve water quality management as well as to accomplish European regulations.

In this section we summarize the Catalan experience as a realistic example of adapting European guidelines to manage water taking into account the local/regional reality.

EMISSION CRITERIA				IMMISSION CRITERIA		
European (Directives)	**Spanish**	Description		**European (Directives)**	**Spanish**	Description
76/464/EEC → 2006/11/EC →	RD 995/2000 RD 258/89	Discharges of certain dangerous substances	**WATER FRAMEWORK DIRECTIVE 2000/60/EC** (modified by **Decision 2455/2001/EC**)	75/440/EEC →	Ord. 15/10/90	Surface water quality required for the abstraction of drinking water
91/271/EEC 98/15/EEC →	RD 11/95	Urban wastewater treatment		80/778/EEC 98/83/EC →	RD 140/03	Quality of water intended for human consumption
80/68/EEC		Protection of groundwater against pollution caused by certain dangerous substances		2006/7/EC →	RD 734/88	Management of bathing water quality
				91/676/EEC →	RD 261/96	Protection of waters against pollution caused by nitrates from agricultural sources
				79/923/EEC → 78/659/EEC →	RD 345/1993 Order 16/11/88 RD 927/88 (Annex III)	Quality of selfish waters Quality of fresh waters to support fish life

Figure 2.1: Water Framework Directive scope

The Catalan sanitation plan

During the last 20 years Catalonia has done several efforts in building and maintaining sanitation infrastructures in order to comply with European Directives and to reduce pollution and promote the good quality of water bodies. As a consequence of the Directive 91/271/EEC (40), the Catalan Government approved the *Catalan Sanitation Plan* (7th November 1995). The Plan describes the quality goals for the Catalan rivers. In order to achieve them, the Plan was divided into five programs covering different domains that must be addressed: *(1)* the urban wastewater treatment program, *(2)* the industrial wastewater treatment program, *(3)* the cattle wastewater treatment program, *(4)* the agricultural and diffuse wastewater treatment program, and *(5)* the sludge treatment program.

For the scope of this work, the Urban Wastewater Treatment Program (UWTP) and the Industrial Wastewater Treatment Program (IWTP) take special importance in order to analyse the context of pollution-prevention policies in Catalonia. UWTP consists of two parts: the first one with the aim to define sanitation in communities over 2000 PE (representing an increase up to 300 WWTPs most of them using the activated sludge system); the second one (approved in 2002 and known as PSARU 2002) with the aim to define the most appropriate treatment for the communities with less than 2000 PE (in Catalonia this accounts for approximately 2500 communities). Specific Environmental Decision Support Systems were built to take the most appropriate treatment considering several aspects (5; 51; 157). So lot of progress has been done in Catalonia in order to reduce pollution thanks to high investments in new infrastructures.

More recently, and due to the requirements established by the European Directive 2000/60/EC (43), the ageing of sanitation infrastructures and the bad operation of some treatment plants as a consequence of diverse types of arriving wastewaters apart from domestic *e.g.* industrial, agriculture, pluvial, *etc.*, the Catalan Government approved a new UWTP known as PSARU 2005. It substitutes PSARU 2002 and links directly the urban wastewater treatment program with the industrial wastewater treatment program. Firstly, the Program outcrops the need to execute enlargement, improvement, adaptation and remodelling of the existing treatment plants to reach the new quality goals. Secondly, it pays special attention to the industrial component of urban WWTPs in order to facilitate the connection to the public system of those industries and/or industrial parks that accomplish the requirements[2]. The program establishes

[2]In Catalonia the Decree 3/2003 - consolidated text of 6/1999 Law - imposes the connection to public system unless the competent organisms considers and authorizes the discharge into the receiving media claiming more safety, that is to prevent damage to the WWTP and consequently to the river.

two temporal scenarios to achieve the new requirements (2006-2008 and 2009-2014) and prioritizes two elements: planning (according to the timetables of the mentioned Directive 2000/60/EC) and economic instruments.

The high investments in sanitation infrastructures have been able to break the link between growth (measured in terms of urban and industrial development) and environmental degradation. But the economical consequences are undeniable: the operation, maintenance, preservation and improvement of these infrastructures generate more and more investments. In this way, it is necessary to establish an equilibrium point among the will of guaranteeing the quality of treatment and environment, with a suitable repercussion of costs that should be self-contained through water canons and other economic taxes.

Accordingly, PSARU 2005 together with the IWTP (known as PSARI 2003) decidedly aim to regulate wastewater discharges, according to their impact into the water bodies (emission and immission based strategy) through some economic instruments imposed to industries (economic based strategy)[3].

2.2 Integrated wastewater management in river basins

Currently, when studying industrialized basins, there are at least three principal components of the system that one must take into consideration: the sewer system, the WWTP and the receiving water (*e.g.* the river) (37; 38; 68; 81; 125; 163; 176; 203). These elements are only a part of the global water system which comprises other natural (*i.e.* atmosphere, groundwater, runoff, sea, *etc.*) and anthropogenic (*i.e.* drinking water production, agriculture, households, system administration, *etc.*) components; the integration of these components comprises the so called Urban Wastewater System (UWS).

As the focus of this thesis lies on the effect and management assessment of industrial discharges, apart from these three subsystems, we will make special emphasis and include in the discussion the industrial component. Naturally, some of the other elements of river basins, although not directly included in the scope of the following sections, they are inherently present when describing the components' interactions.

[3]The Administration Agent depicted in Chapter 5 intends to exemplify this combined policy.

2.2.1 Components

Sewer system

The main issues that the sewer systems address are

- drainage and sanitation, and
- flood protection (60; 163).

For the purposes of this thesis, we only discuss hereby the drainage and sanitation function. This functions entails the transport of both the rain water and the wastewater directly to the receiving media or to a WWTP.

Fundamentally, there are two types of sewer systems:

1. *Separate sewer systems* have two net of pipes for transporting the water, one for the rain water and one for wastewaters. The main advantages of this kind of system are:

    - the wastewater is not diluted during rain so it can be treated more efficiently, and
    - no combined sewer overflows can occur, reducing the amount of pollution leaving the sewer system.

    Some of their disadvantages are the higher construction costs, the risk of misconnection, sudden and strong hydraulic impact to rivers, and higher heavy metal load to the receiving water (125).

2. *Combined sewer systems* have only one pipe that collects and transports together the stormwater and the different types of wastewater (*e.g.* industrial, household, runoff, *etc.*). The advantage is that only one pipe needs to be constructed. During dry weather only sewage from households and industry is transported to the WWTP. During a light rain event the capacity of the sewer allows the transport of stormwater and wastewater to the WWTP. However, one disadvantage can arise since, considering that the hydraulic capacity of the system is not surpassed, during rain events the flow to the treatment plant is increased while the pollutants are diluted, which reduces the efficiency of the treatment plant. Another problematic situation of combined sewer systems occurs when the flow in the sewer system becomes higher than the hydraulic capacity of the pipes or the WWTP (*i.e.* during heavy rain events the hydraulic capacity of the sewer system and the

WWTP is exceeded). In these cases, the water leaves the system *via* emergency exits, or Combined Sewer Overflows (CSOs) and enters the receiving water without treatment, causing acute pollution periods at the discharge point. In order to reduce the amount of combined water spilled at the CSOs, storm tanks are built in the system, to store a certain volume of storm water before the CSOs start to spill. In this way, both the frequency and the volumes of spilling can be reduced.

Thus, the construction of pluvial or storage tanks in the sewer system is not rare, with main functions of:

- Laminating the inflow to the WWTP, that is, to retain the flow during the maximum production of wastewater and releasing the flow when minimum production.
- Retaining punctual polluting episodes and laminating them in order to reduce the impact to the WWTP.
- Decreasing overflows when rain episodes (retaining the peaks during rain periods and releasing them during dry weather).

Wastewater treatment plant

As mentioned previously, one of the main functions of the sewer system is to transport wastewater into a treatment plant. The type of treatment will depend on several factors: the characteristics of arriving wastewater, weather conditions, level of treatment to be achieved, costs, *etc.* Besides the type of treatment, the objective is to treat wastewater before arriving to the receiving media in order to prevent ecological damages.

Urban wastewaters are mostly treated using the *activated sludge system* in which the main treatment is performed by several types of bacteria (189). The treatment performance of these bacteria depends directly on the type and fluctuations of the inflow wastewater. The quality and variability of wastewater received at the sewer and then transported to the WWTP depends mainly on the percentage and composition of industrial wastewaters that are discharged in the combined sewer system together with domestic wastewater; for this reason industries are an important part of the urban wastewater system to be considered when proposing an integrated management of the system.

Figure 2.2 shows a schematic overview of a simple activated sludge plant composed by a pre-treatment, primary treatment and secondary treatment (*i.e.* biological) in which the removal of nutrients and organic matter occurs, and the sludge is separated from the effluent in a secondary clarifier or settling tank (189). As shown in Figure 2.2

part of the sludge (Recycle Activated Sludge –RAS–) settled in the clarifier is recycled into the treatment system to preserve an optimum concentration of micro-organisms, while the rest (Waste Activated Sludge –WAS–) exits the system.

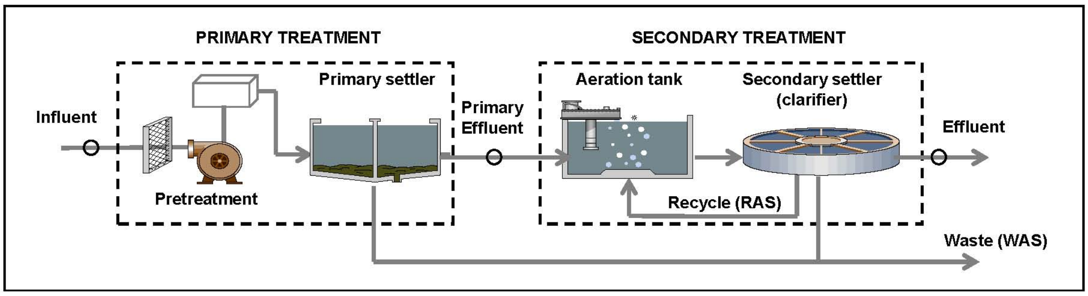


Figure 2.2: Conventional WWTP scheme: *activated sludge system*

The most common WWTP operational states are classified in Figure 2.3. Operational problems at the secondary treatment, specially those with a biological origin, particularly bother WWTP managers. They involve complex microorganisms communities whose dynamics is quite unpredictable.

These problems are briefly described in (54); for a full description of the biological operational problems see (118). The available quantitative (on-line, off-line) and qualitative data permits to characterize and evaluate the WWTP operation and thus to diagnose the abovementioned problems[4]. Table 2.1 list the information available at WWTPs, briefly described as follows:

Quantitative data (118):

- *On-line data* provided by sensors: flow rates (influent, primary effluent, effluent, aeration, recycle, recirculation and wasting) and physical parameters *i.e.* pH and Dissolved Oxygen (DO).

- Quantitative data provided by the *analytical determinations* of samples collected daily from different locations in the plant: organic matter (Chemical Oxygen Demand – COD – and Biochemical Oxygen Demand –BOD–), Suspended Solids (SS), turbidity, Nitrogen (N) and Phosphorous (P), Temperature (T), conductivity, greases and oils, metals or other inhibitors, V30 and biomass concentration

[4]The information hereby summarized conforms the data bases that can then be used to infer knowledge for environmental decision support (see Chapter 6).

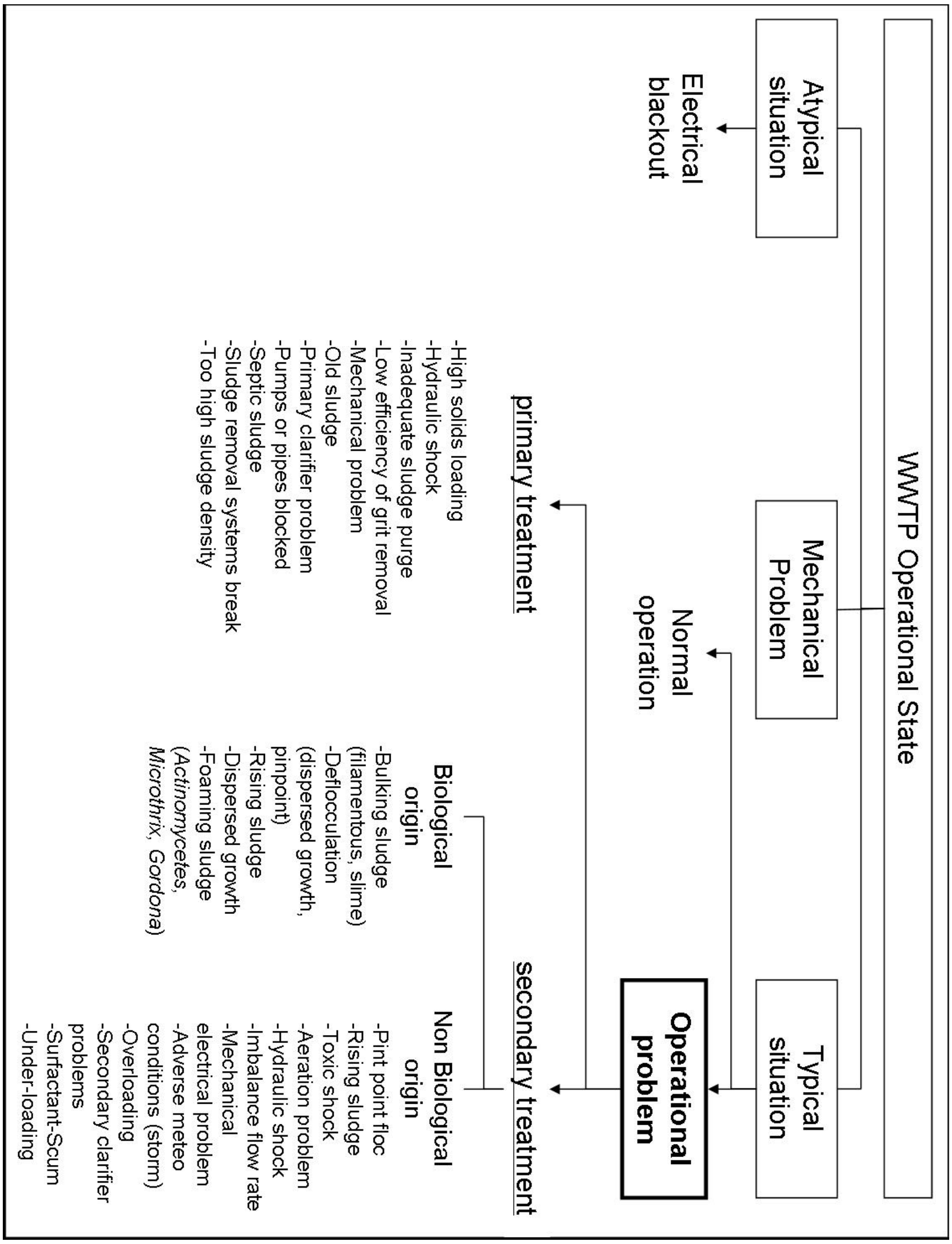


Figure 2.3: List of WWTP operational problems

Table 2.1: Quantitative data measured in the WWTP

Source	Variable	Sampling location
Analytical (off-line)	COD, BOD, TSS and Turb Ammonia (NH_4^+), TKN, NO_2^-, NO_3^-, P, T, Cond, greases and oils, metals, inhibitors	Influent, primary effluent and effluent
	MLSS, MLVSS, V30	Aeration tank and recycle
Sensors (on-line)	pH	Influent and effluent
	DO	Aeration tank
	Flow rates (Flow)	Influent, primary effluent, effluent, aeration, recycle, recirculation and wasting
Global (calculated)	SRT, SVI, F/M, HRT, % COD, BOD and SS removal of primary, secondary and overall treatment	–

(in terms of Mixed Liquor Suspended Solids –MLSS– and Mixed Liquor Volatile Suspended Solids –MLVSS–). For a good monitoring four sample points are defined: influent, primary effluent or secondary influent, aeration tank and final effluent.

- Combinations of quantitative data which allow calculating *global process state variables*: residence time, Hydraulic Residence Time (HRT), Sludge Volume Index (SVI), % of COD, BOD and SS removal of primary, secondary and overall treatment.

Qualitative data (118):

- *Microscopic determinations*: are usually measured once a week and consist of floc characterization (morphology, average floc size, effect of filaments on the floc and overall evaluation of the floc quality), microfauna (protozoa and metazoa) identifications and counting, and filamentous bacteria identification and counting.

- *Macroscopic observations*: refer to observational information obtained in-situ about plant performance, quality of biomass and settling characteristics (V30 test) (usually a daily quality report is available at WWTPs).

Receiving water (river)

Although several types of receiving waters can be distinguished at river basins (*i.e.* lakes, sea, streams, rivers, *etc.*), rivers are the most frequently sinks for urban wastewater. Rivers provide a mean of transport, recreation, fishing, drinking water production, irrigation and are an habitat for aquatic fauna. For all of these reasons water taken from these sources must be returned in the river maintaining an *acceptable* quantity and quality. The quality required depends on the expected use of water; since a combination of water uses can coexist in the receiving water, it is desirable that the minimum quality is determined by the most rigorous water use.

Apart from the inputs received, the river water quality depends on the physical transport and exchange processes (*i.e.* advection and diffusion/dispersion) and biological, biochemical or physical conversion processes between the water column and the sediments.

Water quality is often characterized according to the following parameters (164):

- Physical: temperature, turbidity, conductivity.
- Chemical: DO, BOD or COD, hardness, pH, alkalinity, nutrients (N and P), toxic compounds, organic volatile compounds.
- Biological/Ecological: biocenosis of bacteria, plants and animals, coliform bacteria and variety and complexity of the food chain.

It is clear that all these parameters influence each other and that several factors should be looked at when judging the water quality. The combination of several criteria leads to a classification of the river as having *very good*, *good*, *mediocre*, *deficient* and *bad* ecological quality (which is a combination of physical, chemical and biological parameters) (43).

2.2.2 Interactions and most common problems

Several relations and interactions exist between the system components. The multiple effects that emerge due to the existent relations between the components can be related to:

- The *flow* of water (with both quality and quantity being important), such as the effect of CSO spilled on water quality of the receiving media, or the effect of WWTP effluent into the river, or the effect of the quality and quantity of sewer system wastewater variability delivered to the WWTP.
- The *quality* of water, that is every change of quality in an upstream compartment (*i.e.* sewer system or WWTP) will have a more or less pronounce effect on

downstream compartment (*i.e.* WWTP or river). Table 2.2 summarizes some of the most important impacts related to water quality on the receiving media according to the most important kind of pollutants they can receive from upstream compartments of the urban wastewater system. It is important to note that there is still lot of research to be done in order to describe the feedback effects between the components (*e.g.* such as the several pollutants and the receiving media).

- *Backwater* effects, that is, the reduction of some infrastructures capacity (*e.g.* pluvial tanks, pipes, *etc.*) due to the water held or pushed back by or as if by a dam or current.

Obviously, apart from these relations between chemical and physical processes of several UWS components, many other connections exist arising from the human behaviour component, technical and legal measures, economic instruments and many other indicators (104).

The interrelations of the presented three subsystems lead to some particular problems. The most frequently modelled problems which are referred in the literature (37; 81; 162; 163) are summarized in Table 2.3. Table 2.3 go over the main processes involved at each subsystem and the state variables most commonly studied. As follows:

- *Toxic peak loads through unionized ammonia*: ammonia is, depending on pH and temperature, in chemical equilibrium with unionized ammonia which is toxic to fish. Therefore, the discharge of ammonia from the UWS is often decisive when the oxygen concentration in the river is not a problem (162). The peak load in the CSO discharge is caused by short-term hydrodynamic effects in the sewer system, whereas maximum concentrations in the receiving water are induced just after the inflow to and the mixing with the receiving water. Since the rainfall-runoff process in the natural catchment area is significantly slower than in the urban area, the peak load in the CSO discharge and the minimum dilution capacity at minimum flow rate in the river coincide in the initial phase of the overflow event. The WWTP processes become only significant when the nitrification process or the secondary clarifier is overloaded.

- *Hygienic impact (Fæcal coliforms)*: *Fæcal coliforms* are an indicator for hygienic deficiency in the river. For the receiving water the impact matters if the area is a bathing, water extraction or fishing place.

- *Oxygen depletion* in the receiving water is important (both for the water body and the sediment) since affects the activity of all aquatic fauna and life (*e.g.* fish

Table 2.2: Effect of key pollutants as a result of the interaction with the receiving media. Adapted from (33; 162; 163)

Contaminant	**Environmental effects**	**Ecological Impacts**[a]	**Affected water use**[b]
OXYGEN DEMAND:			
COD from CSOs and WWTPs	DO reduction Biomass accumulation	3, 4 1, 2, 7	A, B, D, E A
NH_4 from CSOs and WWTPs	DO reduction Biomass accumulation	3, 4 1, 2, 7	A, B, D, E A
NUTRIENTS:			
N_{tot} from CSOs and surface runoff	Enrichment	1, 2, 4, 7	A, B, C, D, E
P_{tot} from CSOs and surface runoff	Enrichment	1, 2, 4, 7	A, B, C, D, E
TOXICANTS:			
NH_4 (+ pH + T)	Toxicity	2, 3, 4	D
Metals	Toxicity	2, 3, 4, 7	D
Acute	Toxicity	2, 3, 4, 7	D
Cumulative	Toxicity	2, 3, 4	D
Organic micropollutants (cumulative)	Toxicity		
HYGIENE:			
Faecal bacteria	Public health Biomass	1, 2, 7	A, B, D
PHYSICAL:			
Temperature	T rise + long term change	1, 2, 5, 6	D
Suspended Solids	Blanketing + harm to fish	4, 6	A, B, C, D, E, F
Flow	Washout; morphology changes	2, 4, 7	D
Conductivity	Excess dissolved solids	2, 5, 7	A, D, F

[a]The ecological impacts are referred to ecosystem characteristics: 1.Energy dynamics; 2.Food web; 3.Biodiversity; 4.Critical species; 5.Genetic diversity; 6.Dispersal and migration; 7.Ecosystem development

[b] Beneficial receiving water uses affected by contamination are coded as follows: A.Water supply; B.Bathing; C.Recreation; D.Fishing; E.Industrial water supply; F.Irrigation

Table 2.3: Typical problems modelled: processes and state variables involved (163)

Goal function		Sewer system	WWTP	Receiving water
Toxic peak loads (NH_3)	P	Rainfall-runoff, hydrodynamics, advection/dispersion	Transport, mixing, nitrification	Mixing
	SV	N_{tot}(=NH_4, "worst case")	NH_4, X_{BA} (autotrophic bacteria)	NH_4, pH (measured)
Hygienic impact (Faecal Coliforms)	P	Rainfall-runoff, hydrologic analogy, mixing	-	Transport, mixing, "decay" incl. Various removal processes
	SV	FC	$FC_{effluent}$=constant	FC
Oxygen depletion	P	Rainfall-runoff, hydrol.analogy, mixing, sedimentation in CWRT	Transport, mixing, conversion with ASM1, sedimentation in SST demand	Transport, mixing, conversion, aeration, sediment oxygen
	SV	COD, BOD	COD-fractions	BOD-fractions, DO

P: Processes; SV: State Variables
FC: Faecal Coliforms, SST: Secondary Settling Tank, CWRT: Combined Water Retention Tank

cannot stand oxygen depletion below critical levels for longer periods of time; oxygen depletion progress can lead to *hypoxia*).

To sum up, wastewater discharges' impacts, in which industries are an important source of nutrients and pollutants, can be grouped into chemical, bio-chemical, physical, hygienic, aestethic, hydraulic and hydrologic, and further classified in terms of duration as acute, delayed or accumulating (162). Accordingly, the *flow* of water can reveal problems like infiltration, exfiltration, WWTP overload, hydraulic stress to receiving waters, *etc.* Organic matter, by means of BOD and COD, may indicate organic pollution, hence oxygen depletion and CO_2 emission. Finally, nutrients (N and P) can reveal potential eutrophication in receiving waters. Moreover, the biggest complexity relies on the synergetic effects to aquatic organisms and to identify the critical combination of receiving water properties and urban catchment characteristics (33).

Accordingly, in the following section a brief description of the trends in modelling for water quality management is explained.

2.2.3 Current approaches and challenges

Mathematical modelling in the IUWS has a long tradition, especially the modelling of the separate subsystems. Traditionally, wastewater treatment facilities and hydraulic infrastructures have been managed individually by taking into account the characteristics of water before and after the treatment at a particular facility. Up to the date, there is a long modelling tradition of sewers, treatment plants and receiving water, describing the performance according to the individual needs and objectives. The individual elements of the system have been typically build using deterministic descriptions of the fundamental mechanisms and processes (*e.g.* rainfall-runoff, hydraulics in sewer systems, water quality and pollution transport in sewer systems, wastewater treatment and modelling of quality changes in rivers and other receiving waters) (163).

The enforcement of the WFD by European countries (§2.1.2), which claims for the reconsideration of a river basin scale to manage water and wastewater resources, has induced the movement from such individual consideration of system performance to an integrated management of the urban wastewater system. Integrated mathematical modelling approaches have been used to allow the wastewater system to be considered one single system. The components of the system (*i.e.* sewer, treatment plant and river) are often modelled using complex mechanistic models. The complex equations used to model the system have to be solved using advanced numerical integration algorithms with a high computational burden (203), so in most of applications, these models result to be impractical for use in long-term simulation or in optimization problems. Furthermore, the WFD explicitly mentions the ecological integrity as an important goal, whereas ecological modelling and predictions of ecosystems behaviour are still a problematic issue. Whereas systems have been designed for static/stationary loading, real systems are operating under dynamic loading. Immission-based Real Time Control (RTC) has been suggested as a proper instrument to help fulfilling the WFD requirements (37; 176; 203) by means of building integrated mathematical models for control and evaluation.

Several problems are encountered when creating such models and some solutions such mechanistic surrogate models and model reduction has been proposed, all of them with the purpose to simplify the models to be more operative. To mention only some examples, the integration of the sewer system, WWTP and river has been applied in different catchments *e.g.* (37; 38; 68; 125; 155; 176; 203) using sequential or simultaneous integration of the models.

The majority of the authors mentioned before recognized some problems and/or disadvantages when building these numerical tools:

- Interface problems between submodels, ranging from the different time resolution between different processes to multiplicity of variables used. The range of time constants in the system goes from tens of seconds for oxygen and flow dynamics in treatment plant and sewer, respectively, and up to months for population dynamics in treatment plants and rivers. The latter needs further development of consistent sets of model parameters in the various subsystems in order to dynamically run them without external definition of conversion at the interfaces (163).

- Testing of integrated models: measuring campaigns to support such individual and holistic identification of integrated models may become huge as there is both a temporal and a spatial dimension to consider. The development of mechanistic models and their calibration requires a lot of data making campaigns very costly.
- Uncertainty: the results of individual models have an error threshold *w.r.t* reality as they are built principally using deterministic models and default variables. This uncertainty increases when integrating the models. Moreover, there is an inherent uncertainty in modelling these large complex systems (mainly if they imply natural ecosystems).
- Problem oriented modelling: it is vital to analyze carefully what the problem of the system or the receiving water is and based on this formulate the goal of numerical modelling. The complexity of the model will depend on the goal to be achieve, and it is important to formulate it properly as the complexity of the model is a limiting factor for the simulation time.

A step forward in the integrated management of wastewaters is the construction of DSS. DSS are based on the integration of these numerical models (taking into account the knowledge they can provide) with heuristic knowledge (157). Since now DSS have been applied on individual treatment plants (168) designing different control strategies and helping the decision making process at specific situations that may arise in the facility. More concretely, EDSS can play a key role in the interaction of humans and ecosystems, as they are tools designed to cope with the multidisciplinary nature and high complexity of environmental problems (157).

EDSS have to tackle as well with several problems or bottlenecks such as the integration of several sources of data and knowledge, the improvement of knowledge acquisition methods, the sharing and reuse of knowledge, the development of benchmarks of validation and last but not least the involvement of end-users.

This latter approach reflects the current trend of building combined models which integrate the ecological and socio-economic dimensions of common-pool resources management in terms of their dynamics and interactions (86). A scientific paradigm that go towards this direction is *intelligent agents* research area (see Chapter 4).

2.3 Conclusions

The conclusions of the above sections can be summarized as follows:

- UWS are an important part of (urbanized) river basins. They are composed by several interconnected elements. One important issue to be tackled by water managers in river basins is water pollution caused by the several sources in the system.

- Among several other sources of pollution (briefly analyzed in this chatper), an outstanding water pollution source, both for their quality and quantity variability, are industrial wastewater discharges. To deal with them, means to understand all the relations, from the sources to the final receiving media. In this way, it is possible to observe how the activities upstream affect water quality downstream, and why an integrated management of the system components is required.

- Several management policies exist *i.e.* immission-based, emission-based, economic-based and combinations of two or more of them. These strategies are formulated under some legislation and regulations. The WFD intends to be a unifying framework with the main focus on *pollution prevention* and *carrying capacity* principles. However, deciding pollution thresholds is not a simple task since there is often a disagreement among whether a toxic or a wastewater substance is or is not safe for the final receiving media.

- Mathematical modelling of UWS has a long tradition. The individual elements of the system (*e.g.* sewer, WWTP and river, principally) have been typically built using deterministic descriptions of the fundamental mechanisms and processes within these elements. The problems of this approach are reported in this chapter. Some of them are being solved while others require complementary and/or different approaches to be overcame. In the field of artificial intelligence the area of *intelligent agents* offers a promising paradigm with a high potential to overcome some of the current complex systems bottlenecks.

Chapter 3

Agent-based applications in environmental management

This chapter is focused on agent-based environmental management applications, more concretely in those water and wastewater agent-based applications. Firstly, it gives an overview of the main agent-based applications in environmental management and, secondly, a review of the main agent-oriented platforms and tools available in the environmental sciences domain.

The literature reports a large number of agent-based applications, which are known under a variety of different but similar names: Agent-Based Modelling (ABM), Agent-Based Simulation (ABS), Agent-Based Social Simulations (ABSS), Multi-Agent-Based Simulation or Multi-Agent Simulation, *etc.* (88). From now we are going to keep and use the terms ABM and ABS.

ABM cover a variety of areas in which several applications are being developed. As follows:

- Business and organizations: manufacturing, consumer markets, supply chains, insurance.
- Economics: artificial finance markets, trade networks.
- Infrastructure: electric power markets, hydrogen economy, transportation.
- Telecommunications.
- Crowds: human movement, evacuation modelling.
- Society and culture: ancient civilizations - anthropology, civil disobedience.

- Terrorism: social determinants, organizational networks.
- Military: command and control, force-on-force.
- Biology: ecology, animal group behaviour (*i.e.* ant colonies, bee colonies, migratory birds, *etc.*), cell behaviour, subcellular molecular behaviour.
- Healthcare: assess disease diagnosis, remote healthcare monitoring, *etc.*
- Land use: land cover change, agricultural land use change, rural landowner decision making, rangeland resources management, forest management, urbanization development.
- Environmental management: natural resources management (*i.e.* water supply/demand, rangeland resources, *etc.*), irrigation, environmental monitoring (*e.g.* water, air and soil), stakeholder behaviour for river basin management.
- Scenario development and emergency decision support: floods mitigation, risk management.

3.1 Review

In (12) a review of various published applications is considered. The review is done from both agent-oriented software modelling and implementation perspectives. Athanasiadis remarks that the applications can use agent-based approaches and methods, either as a metaphor for software design or as an abstraction for software development. The applications (an overall of 23 dating from 1996 to 2004) are grouped in three categories to ease their presentation:

1. *Environmental information and data management* (Environmental Data Management Systems –EDMSs–). In most of environmental problems available data and information is characterized by the following attributes: uncertain, imprecise, incorrect, and spatially distributed. EDMSs are needed to tackle with this kind of information. EDMSs are aimed at managing, integrating or distributing environmental data.
2. *Decision support in environmental problems* (Environmental Decision Support Systems –EDSSs–). Most of the applications in this category use agent methodologies and technologies in a way to make the decision-making distributed and

shared between the different experts and stakeholders involved in specific environmental problems.

3. *Simulation of environmental or ecological systems and processes* (Environmental Simulation Systems –ESSs–). Agent-based ESSs use agents as the structuring blocks for modelling processes and interactions. The growing interest in this technique is due to the possibility to incorporate almost directly and intuitively the behaviour observed in the real world by means of a computational model.

Then, the applications are reported with its main tasks and objectives, the application field, related technologies and principal agent types involved. Next, they are evaluated in terms of their level of Software (SW) design and development (from low to upper level design, and from objects to agent-platforms implementation, respectively). In Tables 3.1–3.5 (see pp.39–43) we update and rationalize the available agent-based applications in environmental management following partially the criteria used in (12), and continuing the revision from 2005. The classification of applications in one of the three aforementioned categories (*i.e.* EMS, EDSS and ESS) is not always obvious, since the boundaries between the three categories are intertwined and not always clearly discriminated. The overview of applications is presented chronologically ordered (from the oldest to the newest published references). Four columns have been added to better describe the systems reviewed. These columns make reference to:

Software design From this aspect it is possible to analyze the use of agent-related technologies in software design and modelling. That is, how the agent's concept is used. According to Athanasiadis (12) four levels of agent's design complexity can be distinguished:

(1) At the lowest level there are systems that use some agent-alike *entities*.

(2) In the second level the systems are modelled using agents (a model), typically involving Unified Modelling Language (UML) design.

(3) The third level involves agents for software specification, that is the use BDI (Belief-Desire-Intention architecture) (161), LORA (Logic of Rational Agents) (216) or similar techniques.

(4) In the fourth level the systems adopt a sophisticated agent-oriented software design process as Gaia (218) or Tropos (85).

Software development From the point of view of software implementation four levels of agent-related technologies can be identified:

(A) Implementation with objects.

(B) Implementation with software agents, typically dealing with FIPA standards (http://www.fipa.org).

(C) Implementation using available agent platforms such as JADE (Java Agent DEvelopment framework), ZEUS, JACK, *etc.*

(D) Implementation using an own platform.

Implementation In this column we refer to the system's implementation phase or stage. That is, if the reviewed systems are in the design phase or at the beginning of the development, partially or fully implemented, in progress, *etc.* Somehow it completes the information give in the 'software development' column.

Validation In this column information on whether the agent-based system has been or not tested is given. In computer modelling and simulation, validation is the process of determining the degree to which a model or simulation is an accurate representation of real world from the perspective of the intended uses of the model or simulation.

As follows, a brief explanation of each of the applications reviewed is provided. In this review we have only considered those applications related to environmental management issues; other domains such as economics (47; 98; 188), telecommunications (32; 212), healthcare (10; 95; 132), manufacturing (39; 150), military support (198), *etc.* sustain the suitability of agent-based applications in complex domains. However, although the intention is to present only those agent-based applications related to environmental management issues, some of the applications are either not developed exclusively with agents or they do not deal solely with environmental management applications.

The ***DAI-DEPUR*** system applies distributed artificial intelligence techniques in a DSS for supervising a WWTP. The processes of the plant are represented by agents, which collaborate in a layered architecture (172). This supervisory integrated and distributed architecture proposes the integration of several interacting subsystems or agents, and the combination of problem solving capabilities, reasoning as well as learning tasks in a single structure. A real world application was delivered later in atl-EDAR (173).

In the ***EDS*** (*Environmental Decision Support*) application an agent community is used for supporting the decision-making process related with environmental assessment, planning, and project evaluation. Specifically, the *EDS* system provides assistance to project developers in the selection of adequate locations of their projects (*e.g.* roads, industries, hospitals, *etc.*), guaranteeing the compliance with the applicable regulations and the existing development plans as well as satisfying the specified project requirements and the fulfilment of applicable regulations according to the location (115; 116).

The ***SAEM*** system (*a Society of Agents in Environmental Monitoring*) proposes the use of robotic agents that collaborate for monitoring and evaluating the pollution on a power plant chimney (177). Specifically, a simulated application of small flying robotic agent societies (helicopter models) is assigned to go around a chimney in order to sample the pollutant cloud and to send values to a central processing unit which builds a global map. This map is then transformed into an image that holds information about cloud direction, pollutant concentration, *etc.* allowing decision makers to evaluate and change the burning conditions of the power plant.

In the ***ESAT-WMR*** system (*Expert System and Agent Technology to Water Mains Rehabilitation*), the agent-based decision support tool reported intents to support a U.K. water company in its water mains rehabilitation decision making processes. A community of collaborative agents models the tasks and interactions of the water company and its associates, and, ultimately, assesses alternative strategies for the pipes network rehabilitation (64; 65).

The ***IDS-DAP*** system (*Intelligent Decision Support System for Differentiated Agricultural Products*) is a DSS applied for the selection of agricultural product penetration strategy. It incorporates distributed multi-criteria analysis models. Concretely, the multi-criteria method UTASTAR is applied to the multi-criteria consumer preferences in order to determine the criteria explaining each of the consumer's choices into consumer agents participating in a particular market research (120; 121).

The ***FIRMA*** project (*Freshwater Integrated Resource Management with Agents*) applies agent-based modelling for the integration of natural, hydrologic, social and economic aspects of freshwater management. A variety of agent-based models has been developed for simulating consumers, suppliers, and government, and their interactions at different scale of aggregation. One of the *FIRMA* test cases has been applied on the Thames River to explore the effects of precipitation and temperature on water availability and household demand (27). In this case, water consumer agents communicate with each other, sharing perspectives in the form of endorsement (130).

The ***SHADOC*** system (French acronym for *Hydro-agricultural Simulator describing Organization and Coordination Modes*) uses agents for simulating the behaviour of the stakeholders and the farmers involved in the irrigation of Senegal valley (24). The model constitutes a virtual irrigated system which can already be used as a tool to test hypotheses of social organizations and institutions. This is still a theoretical simulator somewhat specific to the Senegal River Valley even though it has been designed to be able to deal with other contexts.

EDEN-IW (*Environmental Data Exchange Network for Inland Water*) is a system that aims to provide citizens, researchers and other users with existing inland water data, acting as a one-stopshop (73). *EDEN-IW* exploits the technological infrastructure of *Infosleuth* system (138; 154), in which software agents execute data management activities and interpret user queries on a set of distributed and heterogeneous databases. Also, *InfoSleuth* agents collaborate for retrieving data and homogenizing queries, using a common ontology that describes the application field. *EDEN* pilot demonstration enables integrated access via web browser to environmental information resources provided by offices of the connected agencies. The demonstration focuses on information relating to remediation of hazardous waste contamination.

WaWAT (*WasteWater Agent Town*) employs several co-operative agents who make use of case-base reasoning, rule-based reasoning and reactive planning to support supervision and control of wastewater treatment plants (45). It uses the WaWO ontology (*Waste Water Ontology*) (46) which provides a set of concepts that can be queried, advertised and used to control agent cooperation.

The ***BUSTER*** system (*Bremen University Semantic Translator for Enhanced Retrieval*) utilizes ontologies for retrieving information sources and semantic translation into the desired format (133). This approach can be applied when the information can be accessed by remote systems in order to supplement own data basis. The *BUSTER* approach provides a common interface to heterogeneous information sources in terms of an intelligent information broker. A user can submit a query request to the network of integrated data sources (*e.g.* as shown in a query example sampling information about the land use of a specific site).

Adour is a bargaining model to simulate negotiations between water users in a river basin (190). A formal computable bargaining model of multilateral negotiations is applied to the Adour Basin case, in the South West of France, with seven agents (three "farmers", two "environmental lobbies", the water manager, the taxpayer) and seven negotiation variables (three individual irrigation quotas, the price of water, the sizes of three dams), in order to negotiate alternatives of water use. A sensibility analysis is conducted to quantify the impact of the negotiation structure (*e.g.* political weights of players, choice of players, *etc.*) on simulations outcomes. The final aim is to provide a better understanding of the complex interrelations between the various components of the modelled system: preferences of stakeholders over negotiated variables, the role of exogenous (*i.e.* hydraulic and budgetary) constraints in the bargaining game, the consequences of the structure of negotiation (*e.g.* decision rule, players' weights, dimension of the issue space *etc.*) on the bargaining outcome, *etc.*

DIAMOND (*DIstributed Architecture for MONitoring and Diagnosis*) adopts an agent-based architecture for distributed monitoring and diagnosis (4). Industrial diagnostic systems aim at anticipating the occurrence of failures or, should failures have occurred, at detecting them and identifying their cause. *DIAMOND* will be demonstrated for monitoring of the water-steam cycle of a coal fire power plant, and for integrating a diagnostic system with an existing process control network.

The ***MAGIC*** system (*Multi-Agents-based Diagnostic Data Acquisition and Management in Complex Systems*) was created with the same purpose as *DIAMOND*. Even if it is not targeted only for environmental applications, its objective is to develop a flexible multi-agent architecture for the diagnosis of progressively created faults in complex systems, by adopting different diagnostic methods in parallel. *MAGIC* has been demonstrated in an automatic industrial control application (105).

A quite similar system that uses software agents for accessing environmental data is ***NZDIS*** (*New Zealand Distributed Information System*). *NZDIS* (62; 159) has been designed for managing environmental meta-data in order to service queries to heterogeneous data sources. *NZDIS* software agents are used for submitting queries to environmental databases in a seamless way. Agents receive and reply to requests for services and information by means of a high level declarative agent communication language, whose message contents may be expressed in terms of formal ontologies that describe the vocabularies of various domains.

The ***D-NEMO*** experimental prototype, installed in the Athens Air Quality Monitoring Network, uses agents for the management of urban air pollution (103). *D-NEMO* agents incorporate classification and regression decision trees, case based reasoning and artificial neural networks for forecasting collaboratively air pollution episodes.

The ***RAID*** system (*Rilevamento dati Ambientali con Interfaccia DECT*) deals with pollution monitoring and control in indoor environments. *RAID* exploits the general architecture of Kaleidoscope that uses "entities" for the dynamic integration of sensors (126). The system is based on innovative sensors and wireless communication. It includes a knowledge-based supervisor aimed at identifying pollutant sources.

AqEcAA (*Aquatic Ecosystem Simulation with Adaptive Agents*) presents a conceptual framework simulating the aquatic food web and species interactions by using adaptive agents (165). It provides a realistic framework for ecosystem simulation, evolving ecosystem structures and behaviours by emerging, submerging, interacting and evolving ecological entities.

The ***CATCHSCAPE*** system (28) deals with the irrigation of northern Thailand, using agents for representing all entities related with the hydrologic basin. Agents incorporate models for the determination of aquatic reservoirs with respect to future changes in drought conditions and changes in commodity prices, and farmer behaviour.

The ***SINUSE*** application (74) employs agents to model the Kairouan water basin. *SINUSE* agent-based system investigates the consequences of human behaviour in the availability of aquatic resources by simulating physical and socioeconomic interactions on a free access water table. *SINUSE* is considered as a first step in the use of MASs for groundwater studies, and it has proved the relevance of taking local and non-economic interaction into account in the case of the Kairouan water table.

The ***STAU-Wien*** application (*City-Suburb Relations and Development in the Vienna Region*) aims to study the urban growth of Vienna city and its suburbs. The objective of this work is to simulate prior and future landscape transition processes for the suburban region in the surroundings of Vienna, Austria. A spatial agent model is used for stimulating regional migration and allocation decisions of households and commercial enterprises (112).

The multi-agent model ***GEMACE*** (*Multi-Agent Model to Simulate Agricultural and Hunting Management of the Camargue and its Effects*) simulates the interactions between hunters, farmers and duck population of a habitat. The system investigates the correlations between human activities and the environment and their impacts to the land use and the population of ducks (119).

The ***FSEP*** project (*Forecast Streamlining and Enhancement Project*) is being developed in the Australian Bureau of Meteorology, and uses agents for detecting and using data and services available in open, distributed environment. In *FSEP*'s pilot system (63), agents monitor in real time the current Terminal Area Forecasts (forecasts in areas around airports) and alert forecasters to inconsistencies between these predictions and observations obtained from the Automatic Weather Station data.

The ***CANID*** system employs autonomous agents for simulating the population dynamics of coyotes using the Swarm platform (Swarm Development Group 2001).

The system models territoriality and dominance of canine populations and their effects on population dynamics and supports agent interaction with variable schedules and hierarchies (153). The model is not tied to a specific geographic area and does not account for regional differences among populations (*e.g.* litter size, pack size or territory size). Additional model development may account for this variation with changes in resources among regions.

The ***NED-2*** application, developed by the University of Georgia and the USDA Forest Service, deals with the simulation of forest ecosystems management plans and the evaluation of alternatives. In *NED-2* agents use growth and yield models to simulate management plans, perform goal analyzes, and generate result reports (139). *NED-2* uses blackboard architecture and a set of semi-autonomous agents to manage the different modelling tools used.

The ***PICO*** project (151) adopts agent-based requirement analysis for a decision support system in the field of integrated production in agriculture. This work focuses on design issues, using Tropos methodology (85) and continuing their developments using software agents.

In ***O_3RTAA*** several software agents co-operate in a distributed agent society in order to monitor and validate measurements coming from several sensors, to assess air-quality, and to fire alarms when needed (14). *O_3RTAA* relies on the agent paradigm for building intelligent software applications, while takes advantage of machine learning algorithms and data mining methodologies for extracting knowledge and customizing intelligence into agents. The system intervenes between the sensors and the experts and undertakes several tasks in order to assist humans in their evaluation. Specifically, system goals are assigned to agents that act as mediators and deliver validated information to the appropriate stakeholders.

In ***AMEIM*** (an *Agent-based Middleware for Environmental Information Management*) software agents undertake environmental data management tasks. The agents in *AMEIM* are capable to fuse and pre-process environmental data. *AMEIM* is a reusable platform, which realizes a generic architecture for developing agent-based systems, operating as a middleware application between environmental data pools and the final users of environmental information. Accordingly, the *AMEIM* system is fully customizable (depending on the requirements of each application) and, as mentioned before, follows an extendable architecture (15). Reasoning capabilities can also be incorporated into *AMEIM* agents for supporting decision-support features.

DAWN (*Hybrid Agent-Based Model for Estimating Residential Water Demand*) is a simulator that integrates an agent-based social model for the consumer with conventional econometric models. It simulates the residential water demand-supply chain and thus, enables the evaluation of different scenarios for policy making. It was used to evaluate five different water-pricing policies for the period 2004-2010 in the metropolitan area of Thessaloniki (13). Its main advantage is that it supports social interaction between consumers, through an influence diffusion mechanism, implemented via inter-agent communication (JADE and FIPA specifications).

FIRMABAR (*FIRMA* stands for *Freshwater Integrated Resource Management with Agents* and *BAR* for *Barcelona*) is an agent-based simulator, within the *FIRMA* project, aimed at simulating urban water management (113). Such simulator provides the policy makers with an additional tool to evaluate alternative water policies in different scenarios. The simulator plays the life of a set of families (agents) on a grid that represents the territory. The global behaviour of the simulation emerges as a result of the interaction of the individual agents through time (nothing in the model specifies the global-level behaviour of the system). The step time in simulations is the month, and there are four central processes computed at each time step.

MANGA is a discrete event simulator (a sequential process of unrelated events) (109). The objective of *MANGA* is to show, over a number of years (12-year period), the evolution of a group of farmer agents with a limited water resource. In *MANGA* the authors demonstrate that agent-based modelling could help negotiations by showing the consequences of water allocation rules with respect to different criteria (*e.g.* the climate of the year, the irrigated area and the level of irrigation).

MABEL (*Multi-Agent Behavioural Economic Landscape*) presents a bottom-up approach to allow the analysis of dynamic features and relations among geographic, environmental, human, and socioeconomic attributes of landowners, as well as comprehensive relational schematics of land-use change (110). The authors adopt a distributed modelling architecture to separate the modelling of agent behaviours in Bayesian belief networks from task-specific simulation scenarios. *MABEL* has a client-server architecture, a key component that allows to simultaneously simulate land-use change over large regions in an efficient and scalable way. It separates the simulation locations from the agents' behavioural models, which simplifies the work required to parameterize these models for task specific use in the distributed modelling environment.

Control-MWS (*Agent-Based Control of a Municipal Water System*) implements a water pollution monitoring system of a simplified municipal water system (*i.e.* a single water reservoir, a single tank, a pump station with only one electrical pump, pipes and valves). It monitors the level and quality of water basically in the tanks and pumping stations, as strategic points to set up control strategies (83). The authors use a distributed control architecture based on automation controllers with an extended firmware that supports intelligent agents. The intelligence of the system is distributed among multiple controllers by placing individual or multiple agents inside the controllers. After setting up some control strategies, simulations are done to predict the results in water quality under these control strategies.

GRENSMAAS is a project that started in the 1990s. Within the scope of this project the researchers (202) presented an agent-based model to evaluate different river management alternatives developed within the previous phases of the project. This agent-based model is coupled with an integrated river model that describes the impacts of river management, such as flood risk, nature development and costs (related to gravel extractions). Thus, the main use of the agent-based model is to investigate stakeholder environment interaction by simulating changing perspectives and behaviour in response to environmental change. The agents are endowed with quantitative goal standards to evaluate their goals. The beliefs of the agents are related to their uncertainty perspectives for evaluating a river management strategy.

DSS MAS-GIS (*Decision Support System coupling Multi-Agent System and Geographical Information System*) is a framework developed to manage water in the Mediterranean islands. The MAS-GIS platform makes possible for users to better understand the current operation of the system and the evolution of the situation, while simulating different scenarios according to the selected water policies (*i.e.* best consumer water policies) and the climatic changes hypothesis (201).

PALM (*People And Landscape Model*) was used to simulate seven strategies of crop nutrient management used within a community of households (the model simulates resource flows in rural subsistence communities). *PALM* runs on a daily time step using daily weather data as driving variables. The model uses object-oriented concepts with multiple instances of various sub-models being possible. Consequently, as an example, different crop models (or even the same one) can be run simultaneously in different fields with different parameters (*e.g.* planting dates, *etc.*) for each instance. Its structure, together with the use of Object Oriented Programming (OOP) and agents allow a high degree of modularity, and hence flexibility (122; 123).

DANUBIA is a decision support system embedded in *GLOWA-Danube* project aimed at evaluating the sustainability of future water resources management alternatives, and to evaluate consequences of IPCC (Intergovernmental Panel on Climate Change) derived climate scenarios for the period from 2000 to 2100 (94). *DANUBIA* is a coupled simulation system comprising 16 individual models (26). To integrate the different simulation models *DANUBIA* makes use of object-oriented framework approaches. The agent-based approach, within the overall system, is used to model demography, water consumption and supply infrastructure, thus, to assess and simulate the socio-economic aspects of the water cycle (not the physical processes concerned with the water cycle). For that purpose a simulator -***DEEPACTOR***- was built providing a common conceptual and architectural basis for the modelling and implementation of the socio-economic simulation models in *GLOWA-Danube* (25).

WPMS (*Water Pollution Monitoring System*) is aimed at monitoring water quality for regulatory compliance. The water pollution monitoring system is comprised of several sites/stations in which the water quality is monitored, and when the measurements of certain parameters are exceeded, a warning is sent to the supervisor system. As the sites are geographically distributed, they are modelled in a natural way as intelligent agents that communicate with a supervisor agent who receive the corresponding messages from the sites. A prototype has been designed for future implementation (142). The system can also be used to facilitate response to contamination incidents.

Another application in coupling human and natural systems, in the area of *Land-Use Change Dynamics* (**LUCD**), is given by Monticino *et al.* (129). Land-use change dynamics were simulated for several scenarios, differentiated by the initial distribution of the different agents (*i.e.* landowner, homeowner and government types), and economic model assumptions. The goal of this work was to develop both a specific model for the study area and a general framework that captures essential features of land-use change dynamics. The used of multi-attribute key utility functions are the basis of agent rationality and decision-making.

The **SYPR** project (*Southern Yucatán Peninsular Region project*) aims at modelling and simulation of deforestation in this region. One of the main components is ***HELIA*** (*Human-Environment Integrated Land Assessment*). *HELIA* represents real-world households and their land-use strategies as virtual agents equipped with multi-criteria evaluation strategies and other methods (symbolic regression, and evolutionary programming). Another important component is ***LUCIM*** (*Land-Use Changes In the Midwest*). The latest uses a utility-maximization approach whereby a set of household land-use preference parameters are fitted to the land-change record derived from historical aerial photography (117).

MASQUE (*Multi-Agent System for Supporting the Quest for Urban Excellence*) exploits the versatile potential of multi-agent technology for supporting the development of land-use plans (170). It gives a detailed description of the operation of agents who are part of the system's 'knowledge' component, and then, a prototype application is developed to demonstrate how multi-agent concepts can be used to generate alternative plans. It provides functionality to make inventories of a site, *i.e.* tools to input both spatial and a-spatial data about the study area and its surroundings in order to build up project databases.

The ***Thieul*** simulator was developed with the help of *CORMAS* programming environment (21). The agent-based model has been designed to formalize the interactions between the biophysics dynamics of the natural resources (*e.g.* available water, land, *etc.*) and the socio-economic factors driving the land-use dynamics around the drilling of Thieul village in the sylvo-pastoral area of Ferlo (Senegal).

SIMULAIT WATER was used to analyze urban water trading and water saving incentives among households of differing demographic types. Each agent can mimic the behaviour of individual elements (*e.g.* households) in a system, as well as their interactions (*e.g.* negotiations among households). In this case, agents model individual households and their purchasing and water consumption behaviours (152).

LUDAS (*Land-Use Dynamic Simulator*) is a multi-agent system to simulate spatio-temporal dynamics of coupled human-landscape system (108). The system is aimed at explore alternative scenarios to improve livelihoods and mitigate negative impact of land-use changes, thereby supporting the negotiation process among various stakeholders in land-use planning. Human population and the landscape environment are all self-organized interactive agents that are called upon to perform tasks in parallel (*i.e.* synchronizing actions). The framework provides a platform where many techniques already developed in spatial modelling can be integrated. For instance, the authors nested the bounded-rational decision mechanism (*e.g.* the maximization of parameterized utility functions) with the reflex mechanism (set of reflex rules) to represent the decision making mechanisms of farming households about land use.

3.2 Analysis and discussion

In §3.1 forty-two applications using, in a more or less extent, agent-based technology in the environmental management domain, have been briefly explained. In Tables 3.1–3.5 (see pp.39–43) and 3.6–3.7 (see pp.44–45) a summary is given, respectively, together with some important characteristics used to analyze the systems reviewed. These characteristics are quoted in §3.1 and make reference to *agent software design* and *software development* diffusion.

From the *software design* perspective, thirty of the applications use the notion of an agent to conceptualize the system under study. These are followed by eleven applications that adopt the notion of an agent not only to conceptualize the system but to specify the software as well. Still seven of the applications reviewed use a low level notion of agents, understanding the agents as simple agent-alike *"entities"*. Finally, only three of the applications adopt a more sophisticated agent-oriented software process to design the system. This latest remark suppose that, whereas from 1996 to 2004 only one of the reviewed systems had used an agent-oriented software engineering technique throughout the whole design process (*i.e. PICO*), from 2005 to 2008 two more of the studied systems have used them (*i.e. AMEIM*, *WPMS*). As shown in Tables 3.6–3.7 some of the systems use, in the same application, different levels of software design. If such is the case, both notions considered have been noted.

Following the same perspective (*i.e.* software design), in Tables 3.1–3.5 the agent types (or names) used to model the systems are written. They can be classified in two general categories: one group containing agents that perform specific functions (*i.e.* knowledge base, case-based reasoning, supervisory, data provider, query, broker, ontology, wrapper agents) and a second group containing agents that represent physical objects (*i.e.* pump station, watercourse agent, *etc.*), persons (*i.e.* landowner, household, farmer, taxpayer, hunting manager, *etc.*) or institutions (*i.e.* environmental lobbies, families, government agents, *etc.*). That is, in the first category there are well-known knowledge base, data mining *etc.* tasks, whereas in the second category an *agentification* of several real entities takes place. These latest agents are commonly operated with an specific model describing their behaviour.

From a *software development* perspective, the applications presented are generally developed with an object-oriented language. Sixteen of them implement the system with objects. Nevertheless, twelve of them use agent-based platforms. These platforms are either generic (*e.g.* Swarm, NetLogo, *etc.*) or specific builded platforms (*e.g.* SimulaitWater, DeepActor, *etc.*). Their implementation degree, if known, is generally either partially or fully developed prototype. None of them is reported to be fully implemented as a real-time application.

When analyzing the *validation* step, twenty seven of the applications are validated. As a first-step validation, the most extended method employed to validate agent-based applications is by means of expert validation of the model they use. As a second step,

Table 3.1: Summary of the reviewed systems.

Acronym	**Main tasks and objectives**	**Application Field**	**Related technologies**	**Agents** (names or types)
DAI-DEPUR (172; 173)	Simulation and control of the physical, chemical, microbiological aspects of the activated sludge processes	WWTPs	LISP, G2, GAR, LINNEO$^+$	Knowledge base agents, case-base reasoning agents, supervisory agents
EDS-DAI (115)	Project evaluation and assessment with respect to alternative locations that comply with legal regulations, development plans and satisfy custom requirements	Environmental project evaluation	Distributed Belief Revision, ARCHON	Decision support agents (or evaluation agents), data provider agents (stored in GIS), user interface agent
SAEM (177)	Monitoring the pollutant cloud emitted by a power plant chimney	Atmospheric pollution	Robotic agents	Helicopter agents
ESAT-WMR (64; 65)	Modelling and analysis of elective strategies for urban water supply pipe network rehabilitation	Water supply networks	KIF, KQML, OOP	Interface agent, heuristics agent, information agent, data mining agent, database agent, constraint agent, predictor agent, hot spot agent
IDS-DAP (120; 121)	Market penetration of agricultural products investigation, using multicriteria analysis	Differentiated agricultural products marketing	UML, Visual Basic, TCP-IP, Java	Data analysis agent, brand choice agent, market expert agent
FIRMA & Thames (27; 130)	Agent-based modelling for the integration of natural, hydrologic, social and economic aspects of freshwater management	Water resource management	SDML	Policy agent, citizens
SHADOC (24)	Farmer behaviour and water allocation simulation	Water catchment management	UML, SmallTalk, OOP, Petri Nets, CORMAS, Visual Works®	Pump station, reach, watercourse, farmer agents
EDEN-IW & InfoSleuth (73; 138; 154)	Data integration and homogeneous access provision services	Water resources data	JADE, FIPA-ACL, SQL, RDF, OKBC	DB resource agent, query decomposition agent, ontology agent, broker agent

Table 3.2: (continued) Summary of the reviewed systems.

Acronym	**Main tasks and objectives**	**Application Field**	**Related technologies**	**Agents** (names or types)
WaWAT (WaWo) (45; 46)	A multi-agent cooperation infrastructure for supervision and decision-making in WWTPs	WWTPs s	Ontolingua KSL Server	Dynamic *entitties* (monitoring, modelling, actuator, predictive agents, *etc.*)
BUSTER (133)	Data integration and filtering, querying services	Geographical information sources	OIL, FIPA-OS	Wrapper, mediator, mapper
Adour (190)	Stakeholder negotiation over water use	Water management	BDI	Farmers, environmental lobbies, water manager, taxpayer
MAGIC & DIAMOND (4; 105)	Fault detection in industrial process	Water treatment process and Water steam cycle a power plant	XML, CORBA, FIPA-ACL	Diagnostic agents, data acquisition agents, knowledge acquisition agent, wrapper agents, monitoring agent
NZDIS (62; 159)	Integrated querying services in an open, distributed environment of heterogeneous databases	Environmental data	FIPA-ACL, UML, OQL, RDF	Ontology agent, resource agent, query processing agents, broker agent
D-NEMO (103)	Air pollution incident forecasting	Atmospheric pollution	LALO, KQML	Station agents, model agents
RAID (126)	Pollution monitoring and control in indoor environments	Indoor air quality	UML, Kaleidoscope	*Entities*: manager, sensors, *etc.*
AdEcAA (165)	Simulation of aquatic food webs and plankton species interactions	Food chain	Echo	Phytoplankton species, zooplankton species
CATCHSCAPE (28)	Simulation of the whole catchment features as well as farmer's individual decisions	Water catchment management	UML, SmallTalk, OOP, CORMAS	Crop, farmer, canal, weir, canal manager, river
SINUSE (74)	Physical and socio-economic interactions modelling for simulating demand management negotiations on a free access water table	Integrated management of a water table	UML, SmallTalk, OOP	Plot, water table, farmer
STAU-Wien (112)	Simulation or rural development patterns in the Vienna region	Rural development	UML, ArcInfo, cellular automata, OOP	Enterprises, households

Table 3.3: (continued) Summary of the reviewed systems.

Acronym	**Main tasks and objectives**	**Application Field**	**Related technologies**	**Agents** (names or types)
GEMACE (119)	Simulation of interactions between duch population, farming decisions and leasing of hunting rights	Environmental planning	UML, SmallTalk, OOP, CORMAS	Hunting manager agents, farmer agents
FSEP (63)	Surveillance, forecasting and alert of weather conditions	Meteorology	JACK, RDF-S, DAML+OIL	Wrapper agents, interface agents
CANID (153)	Agent-based simulation of territoriality and cominance of canid populations	Biodiversity-population dynamics	Swarm	*Coyote*, pack
NED-2 (139)	Forest ecosystem management simulation and goal-driven decision support	Forest management	C++, Prolog, HTML	Interface agent, simulation agent, goal analysis, planning agent
PICO (151)	Design system requirements, analysis of organizational complexity, dealing with all the dependencies between the domain stakeholders, and study of natural plant protection techniques	Integrated production in agriculture	Tropos, WEKA	GIS agents, disease behaviour learner, wrapper agents
O_3RTAA (14)	A MAS for monitoring and assessing air-quality attributes, firing alarms to appropiate recipients when needed.	Urban Pollution Control (air)	JADE, FIPA-ACL, Protégé 2000 (exported in RDFS), WEKA, JESS, PMML	Diagnosis agent, database agent, distribution agent, alarm agent
AMEIM (15)	A MAS able to capture and validate environmental data from several external sources	Environmental data monitoring and management	GAIA, AORML, JADE, Protégé 2000, FIPA-ACL	Contribution agents, data management agents, distribution agents, graphical user interface agent
DAWN (13)	Simulation of residential water demand and how water pricing policies affect demand	Water demand management	AORML, 2D grids, JADE	Simulator, meteo, consumer, supplier agents
FIRMABAR (113)	Integrated freshwater assessment in a geographic area by means of water supply/demand simulations (in different scenarios)	Urban water management	SDML, Swarm libraries (Java), OOP	Families, companies, municipalities, government agents

Table 3.4: (continued) Summary of the reviewed systems.

Acronym	**Main tasks and objectives**	**Application Field**	**Related technologies**	**Agents** (names or types)
MANGA (109)	Simulation of decision-making process and of the impact of water allocation on farmer's collective behaviour	Rural development, water resources management	UML	Farmers, water suppliers, crops, climate, information supplier agents
MABEL (110)	Simulation of land-use changes over time and space	Land use	BDI architecture, Swarm, VisualStudio.NET C/ C++, BBN (Bayesan Belief Network)	Policy maker, landowners (farmer agent, ubrban residential agent, forestry agent, household agent, *etc.*)
Control-MWS (83)	Water pollution monitoring system (water quality, energy costs and demand) of a simplified municipal water system	Urban water data management	Simulink tool	Pumping station, tank agents
GRENSMAAS project (202)	Simulation of stakeholder support in under different policy stretegies (nature development, gravel extraction, flood reduction)	Water catchment management	BDI (approach)	Policy makers, citizens, farmers, nature organizations, gravel extractors agents
MAS-GIS DSS (201)	Decision support system framework for water management in the Mediterranean islands coupling a MAS with a Geographic Information System	Water management	CORMAS, ARCGIS, ODBC	Drillings, tanks, water companies, consumers (hotels and homes), and a water police agents
PALM (122; 123)	Simulation of management strategies in a community of households in Nepal (linking decision-making to underlying biological processes in soil nutrient dynamics)	Rural development	UML, OOP	Household, landscape, livestock agents
DANUBIA (DEEP-ACTOR) (25; 26)	Simulation of scenarios and strategies for the future of water in the upper Danube Basin (an integrative DSS)	Water resources management (water supply and groundwater) under conditions of global change	UML, OOP	Farmer agents (maize, meat breed, *etc.*), water supply company and household agents

Table 3.5: (continued) Summary of the reviewed systems.

Acronym	**Main tasks and objectives**	**Application Field**	**Related technologies**	**Agents** (names or types)
WPMS (142)	Water pollution monitoring for regulatory compliance (early stage of research; analysis phase)	Urban water management	FIPA-ACL, UML, GAIA	Monitor, supervisor and control agents
Thieul (21)	Simulation an agro-sylvopastoral context	Integrated natural resource management	UML, CORMAS	Farmers, herders and farmer-herders agents
LUCD (129)	Determining conditions of the interactions between human decisions and natural systems that lead to long-term sustainability of forest ecosystems	Land-use management, forest management	Multi-attribute utility functions	Landowner, developer, homeowner, government agents
SYPR project (HELIA and LUCIM) (117)	Modelling land change and economic decision-making in the United States (LUCIM) and Mexico (HELIA)	Land-use management, forest management	Evolutionary programming, multi-criteria evaluation, symbolic regression	Households agents (agriculturalists types)
MASQUE (170)	Multi-agent planning support system that supports decisions related to complex, uncertain and subjective urban planning problems	Land use (urban)	BDI, UML, Borland JBuilderTM	Facilitation, interface, tool and domain (refer to land-use) agents
SIMULAIT WATER (152)	Simulation and analysis of various pricing and trading policies	Urban water management (supply and trading)	Scripting language	Household agents (low, medium and high)
LUDAS (108)	Spatio-temporal simulation of a coupled humanlandscape system	Land-use and rural development	NetLogo 3.0	Household, landscape, agricultural agents

Table 3.6: Deep analysis of the reviewed systems.

Acronym	SW Design	SW Dev.	Implementation Degree	Validation
DAI-DEPUR	2,3	D	Partial. The rule-based component and the case-based component were implemented, but not interconnected. It was continued in the WaWAT (WaWo) system. Also, a real-world application was delivered in the atl-EDAR system (173)	Is incrementally being done at several points during its development. Whole system validation at three levels (1) simulation of the plant in real time, (2) building-up and testing on a pilot scale plant, and (3) validation on a real plant
EDS-DAI	2	C	The system prototype is under development	Two stages of evaluation: (1) Submission to the relevant group of public (and private) agencies, (2) Incorporation of consulted agencies' opinions
SAEM	2	D	Unkwnon	The use of simulation gives the chance of testing this kind of behaviours without building the real agents
ESAT-WMR	3	D	Partial	No
IDS-DAP	2	A	Unknown	No
FIRMA & Thames	1, 2	A	Full	Validation of model struct. and simulation results with stakeholders (focus groups) (comp. validation)
SHADOC	2	A	Full	Expert validation
EDEN-IW & InfoSleuth	2, 3	C	Partial (EDEN-IW DEMO available)	No
WaWAT (WaWo)	2,3	D	A prototype	Through some case study
BUSTER	2	B	A first prototype	No
Adour	3		Future Implementation in a case study (Adour Basin)	No
MAGIC & DIAMOND	2, 3	A, B	Core toolkit developed	Evaluation examples. Comparison values with simulated offline and online ones
NZDIS	2	B	Full	Unknown
D-NEMO	3	C	Full	Experimental multiagent prototype under simulated real time conditions
RAID	1	A	Unknown	Unknown
AdEcAA	2	A	An example of individual-based adaptative agents simulation system is implemented on the Echo framework	Through a multivariate time-series database for nine lakes different in climate, eutrophication and morphology

Table 3.7: (continued) Deep analysis of the systems reviewed.

Acronym	**SW Design**	**SW Dev.**	**Implementation Degree**	**Validation**
CATCH-SCAPE	2	A	Some prototypes	Comparison of the average simulated yields with those provided by local Thai Agencies
SINUSE	2	A	Full	Two step validation: 1) Extreme tests, 2) Partial sensitivity analysis
STAU-Wien	2	A	Full	No
GEMACE	2	A	Some prototypes	Expert validation
FSEP	2	C	A prototype	Through comparison between observed and forecasted data
CANID	2	C	Unknown	Comp. with other models; sensitivity analysis and calibration methods
NED-2	2	A, D	A prototype	Planned
PICO	4		No	No
O_3RTAA	2, 3	C	Full	In a single meteorological station. Extended validation planned
AMEIM	4	C	Full (AMEIM ver.1.0)	Unknown
DAWN	2	C	Full	Metropolitan Area of Thessaloniki (under 5 scenarios). Expert validation
FIRMA-BAR	2	C	Full	Barcelona and Valladolid (under several scenarios). Expert validation
MANGA	2	A	Full	Qualitative
MABEL	3	C	Full	Against historical data
Control-MWS	1	A	Full	In a municipal wastewater system
GRENS-MAAS	3	A	Partia	Comparison with historical data
MAS-GIS DSS	1	C	A prototype	Expert validation
PALM	2	A	Partial	Two step validation: 1) Comp. with historical data, 2) Expert validation
DANUBIA (DEEP-ACTOR)	2	D	Full (not yet avail. for the interested end users, *i.e.* governm. institutions)	Two step validation: 1) Comparison with observed values; 2) Expert validation
WPMS	4		No	No
Thieul	2	C	Full	Expert validation
LUCD	1, 2		Full (optimization of utility functions)	Comparison with real data
SYPR (HELIA and LUCIM)	1, 2		Full (optim. of utility funct. and use of multicriteria, symb. regression and evol. progr.)	Comparison of experimental data with expert knowledge
MASQUE	3	A	A prototype	Planned
SIMULAIT WATER	1, 2	D	A prototype	No
LUDAS	2	C	Full	Model validation in progress

most of the applications permit to do some simulations and to compare the simulated results against historical and/or observed data (when available). Few of them use other, more sophisticated, techniques (*i.e.* sensitivity analysis, extreme tests or cases).

Chapter 4

Agents, multi-agent systems and argumentation theory: principal concepts

In this chapter a brief review about the theory and practice issues related with the design and creation of intelligent agents and multi-agent systems is provided. When describing the notion of agent Wooldridge (215) proposes to answer some questions related to three important areas: agent theories, agent architectures and agent languages (see Table 4.1). Inhere we provide and discuss an explanation of the main concepts in order to give an answer to these key questions and provide the basis of the application of multi-agent oriented design and operation to our domain.

The areas and questions presented in Table 4.1 answer, in some way, to the general classification of agent technologies, tools and techniques in the following categories (114):

- *Organizational-level*, corresponding at the top level of technologies and techniques able to provide an organizational structure, norms and obligations of complex agent societies.
- *Interaction-level*, corresponding to the technologies and techniques that concern the communication between agents.
- *Agent-level*, corresponding to technologies and techniques concerned only with individual agents, its procedures for reasoning and learning.

Table 4.1: Questions to answer when describing the notion of *agency* (215)

Area	**Description**	**Questions**
Agent Theory	Specifications	1. How are we to conceptualize agents? 2. What properties should agents have, and how are we to formally represent and reason about these properties?
Agent Architectures	The move from specification to implementation	3. How are we to construct computer systems that satisfy the properties specified by agent theorists? 4. What software and/or hardware structures are appropriate? 5. What is an appropriate separation of concerns?
Agent Languages	Programming languages that may embody the various principles proposed by theorists	6. How are we to program agents? 7. What are the right primitives for this task? 8. How are we to effectively compile or execute agent programs?

The aim of this chapter is to overview the different concepts we have used in this thesis *w.r.t* the areas mentioned in Table 4.1. Accordingly, in §4.1 and §4.2 some aspects related to *agent theory* are summarized. In §4.3 the principal notions used to model our system are described covering important concepts of the *agent's architecture* area. Finally, in §4.4 the necessary terminology *w.r.t* the *agent's language* used for their specification is introduced.

4.1 Agent definition and properties

Several definitions and forms to describe and use agents exist in the literature. Among others, Bradshaw (34), Höppner (93), Jennings (99), Luck (114), Nwana (140), Russel (169) and Wooldridge (215), provide particular overviews, going through history, of theory and practice of software agents and their possible classifications. All of them converge in affirming that agent software is a rapidly developing area of research, although sometimes the term *agent* has been overused and employed as a banner.

A general notion of agent is given by Russell and Norvig in (169):

> *An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors.*

This definition match with Wooldridge (213; 215) so called *weak notion* of agent:

> *An agent computer system that is* situated *in some* environment*, and that is capable of* autonomous *action in this environment in order to meet its design* objectives.

Derived from the definitions above mentioned agents might, at least, have to a greater or lesser degree, the following properties:

- ***Autonomy***: the capacity to take decisions based on its perceptions of the environment and the goals it aims to satisfy, without external control (*e.g.* the direct intervention of humans or others). Autonomy is probably the most important and essential attribute of an agent which can be directly inferred from the following properties.

- ***Reactivity***: the capacity of agents to perceive their environment and take actions in response to changes that occur in it.

- ***Pro-activeness***: the capacity to exhibit goal-directed behaviour by taking the initiative (that is, making plans) instead of simply acting in response to their environment.

- ***Social ability***: the capacity of agents to interact with other agents via some kind of *agent-communication language* in order not only to share information but to coordinate actions to achieve goals they could not fulfil on their own. This specific property of agents gives the possibility to solve more complex problems

Apart from these core properties, agents can show other attributes such as:

- *Mobility*: the ability of an agent to move around an electronic network, from one host platform to another.

- *Veracity*: is the assumption that an agent will not consciously communicate false information.

- *Benevolence*: is the assumption that agents will always try to do what they are asked to do.

- *Rationality* is the assumption that an agent will act in order to achieve its goals instead of preventing its goals being achieved. This attribute depicts the idea to *do the right thing*, that is for each possible perception the agent should do the action(s) that are expected to maximize its performance criteria, on the basis of the evidence provided by the percept sequence and its built-in knowledge. The capacity of reasoning and planning (*i.e.* actions are not scripted) gives the agent more flexibility (169).

- *Adaptivity*: the ability to learn and improve performance with experience (also called the learning attribute).

A more interesting but complex notion of agents arises when, in addition to having the properties above identified, common human attributes such as mental and emotional notions (*i.e.* believing, wanting, hoping, fearing, *etc.*), are specified to agents (67).

This *stronger* notion adds a new value and challenge to software agents (100): they become somewhat more than self-contained entities executing software processes that encapsulate some state and able to communicate to each other, moreover they might be able to experience and tackle with emergent behaviour.

Several agents' taxonomies and classifications schemes have been proposed when trying to established a useful and valid categorization of agents (34; 80; 93; 140; 169). Depending on the approach and project-related applications, the different classifications are used simultaneously. However, some of them are considered obsolete with the emergence of new types of agents when taking into account the *strong* notion of agents. The majority of them are classifications using the above agent properties and capacities (general and/or specific). It is important to say that these classifications are not exhaustive nor excluding, since we can have agents that belong, in more or less degree, to several categories. Furthermore, many times the systems are heterogeneous, thus composed by agents of different types.

4.2 Multi-agent systems

The notion of Multi-Agent Systems (MAS) emerges directly from the social attribute of agents. A general accepted definition of Multi-Agent System is given by Wooldridge in (213):

> *A multi-agent system contains a number of agents, which interact with one another through* communication*. The agents are able to act in an environment [...]. When faced with what appears to be a multi-agent domain, it is critically important to understand the type of the* interaction *that takes place between the agents.*

Some of the principal characteristics of MAS are described by Jennings in (99). Most of them are inherited from motivations, goals and potential benefits of Distributed Artificial Intelligence (DAI) discipline:

- each agent has incomplete information or capabilities for solving the problem, thus each agent has a limited viewpoint;
- there is no global system control (the behaviour of the whole system is often not obvious from the outset);
- data is decentralized (MAS are open, without centralized designer); and
- computation is asynchronous (that is, not occurring at predetermined or regular intervals).

These characteristics can be resumed by the general distinguished quality of multi-agent systems: the global behaviour derives from the interaction among the constituent agents, that is, the whole system can be more than the sum of its parts. Although the design phase often comes up at the agent's level (micro-definition), the real aim is to understand the aggregated emerging behaviour and the manifestation of macroscopic properties from micro-interactions. Thus, MAS are increasingly characterized by the study, design and implementation of societies of artificial agents aimed to solve problems. The distribution in several agents is necessary because these problems can be complex or too large to be solved by a single process, or even, they can need knowledge of several domains. Hence, the multi-agent case is ideally suited to represent problems that have multiple problem solving methods, multiple perspectives and/or multiple problems solving entities.

As mentioned before, *sociality* is a key concept of MAS. Generally, an agent-based system contains more than one agent establishing some kind of interaction. The most common patterns of interaction are:

- cooperation (work together towards a common aim),
- coordination (organize a problem solving activity to avoid harmful interactions, thus exploiting only beneficial interactions) and
- negotiation (come to an agreement which is acceptable to all the parties involved) (169).

4.3 Agent-oriented modelling

This section gives an overview of the particular requirements needed for the development of agent systems and which characteristics and agent-oriented development model needs to display. Agent-oriented modelling (named as well Agent-Based Modelling, hereby ABM) provides a new technique for the conceptualization of complex systems (31).

To assess the arguments that allow the designers be more effective means to tackle with, at least, three important mechanisms used to deal with complexity (97):

- **Decomposition**, that consists on dividing the problem into smaller parts which can then be treated in relative isolation (at any given instant only a portion of the problem needs to be considered).
- **Abstraction**, that consists on putting attention on the significant aspects of the problem rather than on details.
- **Organization**, that consists on identifying and managing the inter-relationships between the various problem solving components.

Agent-Oriented Software Engineering (AOSE) is considered as the new paradigm for the development of methodologies to analyze and design today's complex systems (218). Agent-oriented methodologies give support to the analysis, design and implementation of agent-based systems to be adopted in an effective way and thus, to prove that the three arguments abovementioned are suited to develop agent-based systems. Adopting an agent-oriented approach means decomposing the problem into multiple, interacting, autonomous components (agents) that have particular objectives to achieve. Hence, agents, interactions and organizations are the key abstraction models that define the system. Explicit structures and mechanisms for describing and managing the relationships and links between the agents shape the organizational structure.

Various authors have investigated in more detail the particular modelling requirements of agent-based systems (31; 35; 36; 97; 149; 156; 199). As general features, they agree that agent-oriented modelling, in order to give support to dynamic and heterogeneous systems, supports an analysis phase with three models:

1. Agent model (agent internal design): containing agents and their internal structure and mental constructs such as beliefs, goals, plans and actions;

2. Agent interaction model (agent interaction design): specifying the relationships among agents and agent categories; the design of interaction protocols and exchanged messages; and

3. Organizational model (MAS organization design): consisting on the interaction and cooperation processes between the agents, that is, the design of acquaintances and authority relationships amongst agents or agents' roles.

In view of that, although the technologies developed by agent-oriented software engineers attempt to give support to the whole of these models, they can be classified taking into account in which of these levels (agent-level, interaction-level, and organizational-level, respectively) they put more attention or give more support (114).

Inspired by probably one of the most extended agent-oriented software methodology, which is GAIA (218), a further detail on agent-based modelling concepts and steps is provided in the following sections of this chapter (§4.3.1, §4.3.2, §4.3.3). The GAIA methodology is intended to allow the analyst and designer to go from the statement of requirements to a design enough detailed to be implemented (although the methodology itself does not deal with implementation directly). Each step of the methodology facilitates to move from abstract to increasingly concrete concepts, therefore analysis and design can be thought of as a process of developing progressively more detailed models of the system to be constructed.

4.3.1 Agent internal design

This step consists on building the agent model which contains the agents and their internal structure. Firstly, it is fundamental to identify the *agents* and their *environment*. Normally this analysis is quite intuitively, since agents can be seen as the *active entities* in the system that change their own states, whereas the environment is made of *passive elements* that change through the agents actions.

Secondly, is important to characterize each agent defining their motivations and behaviour, including agents' mental constructs such as *belief*, *goals*, *plans* and *actions*. For instance, motivations (*e.g.* interests, preferences, responsibilities, long-term goals, *etc.*) play an important role in the way an agent makes its decisions, mainly when an agent has more than one way of acting in a given situation.

The result of the agent internal analysis and design phase is a model that pictures a collection of agents with the specification of their motivations and plans, and the type of knowledge and belief they require to execute the plans. In this respect, GAIA gives especial support in the analysis and design phase of the agent model for a specific system (218). A key component to build the agent model is the identification and description of *roles*. Figure 4.1 show the GAIA template for roles specification that brings together the four following attributes of a given role:

- *Protocols*: defines a set of standardized procedures, that is, the patterns of data exchanged amongst agents *i.e.* the roles interaction.

- *Activities*: are computations associated with the role that may be carried out by the agent without interacting with other agents.

- *Permissions*: are the rights associated with a role in order to realize responsibilities. Thus, they identify the resources that are available to that role in order to realize its responsibilities (intuitively it indicates what can be used while performing the role). Permissions tend to be information resources.

- *Responsibilities*: determine the roles' functionality. They are divided into two types: *liveness* and *safety* properties. *Liveness* properties describe those states of affairs that an agent must bring about (intuitively state that something good happens), given certain environmental conditions. *Safety* properties are invariants and intuitively state that nothing bad happens.

Role:	*Name of role*
Description:	*Short description of the role*
Protocols & Activities:	*Protocols and activities in which the role plays a part*
Permissions:	*"rights" associated with the role*
Responsibilities	
Liveness:	*Liveness responsibilities*
Safety:	*Safety responsibilities*

Figure 4.1: Template for role schemata as in Zambonelli *et al.* (218)

In Table 4.2 it is represented GAIA's formal notation to express liveness properties in order to help to define the *life-cycle* of the role.

Table 4.2: Operators for liveness expressions

Operator	Interpretation
x· y	x followed by y
x| y	x or y occurs
x^*	x occurs 0 or more times
x^+	x occurs 1 or more times
x^∞	x occurs indefinitely often
$[x]$	x is optional
x||y	x and y interleaved

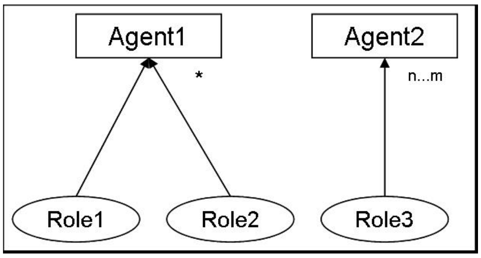


Figure 4.2: A sample agent model

4.3.2 Agent interaction design

This step consists on the detailed definition of the interaction protocols and the content of the exchanged information. For each inter-role interaction a protocol must be defined according, at least, to the following attributes (see Figure 4.3):

- *Initiator*: the role(s) responsible for starting the interaction.
- *Partner*: the responder role(s) with which the initiator interacts.
- *Input*: information used by the protocol initiator while enacting the protocol.
- *Output*: information supplied by the protocol responder during interaction.

Usually the pattern goes with a brief explanation of the protocol purpose (in fact included in the Protocol Name) and the processing activities implied in its execution. The result of this phase is the *service model* (also known as the interaction or cooperation model normally represented using a table). A service is a coherent block of activity in which an agent will engage. Services can be directly derived from the list of protocols, activities, responsibilities and liveness properties of a role. Specifically, we

<table>
<tr><td colspan="2">Protocol Name:
Brief textual description capturing the nature of the interaction</td><td></td></tr>
<tr><td>Initiator:
The role(s) responsible for starting the interaction</td><td>Partner
The responder role(s) with which the initatior interacts</td><td>Input:
Information used by the protocol initiator while enacting the protocol</td></tr>
<tr><td colspan="2">Description:
Textual description explaining the purpose of the protocol and the processing activities implied in its execution</td><td>Output:
Information supplied by the protocol responder during interaction</td></tr>
</table>

Figure 4.3: Protocol definition

must identify the inputs, outputs, pre-conditions, and post-conditions of each service. Inputs and outputs are those from the protocols model. Pre- and post-conditions, representing constraints on services, are derived from the safety properties of a role. By definition, each role will be associated with at least one service (218).

4.3.3 MAS organizational design

This step of ABM consists on designing the acquaintances and relationships between agents or agent's roles. The result is an organizational model that gives an overview of the connections among agents. They do not define what messages are sent or when messages are sent, they simply indicate that communication pathways exist. It is a useful step to identify any potential communication bottleneck which may cause problems at run-time (216).

An acquaintance model may be easily derived from the roles, protocols and agent models. Usually, it is depicted in a graph with nodes corresponding to agent types and arcs to communication pathways.

4.4 Agent's reasoning and communication

In MAS, agents are designed to accomplish particular tasks and they should be able to generate, adopt, drop and achieve their goals (30). For this purpose, agents are equipped with reasoning capabilities expressed in some computational logics or so called *agent languages*. By an *agent language* it is understood a system that allows to program hardware or software computer systems in terms of some of the concepts developed by agent theorists. At the very least, it is expected such a language to include some structure corresponding to an agent. However, it is also expected to see some other attributes of agency (beliefs, goals, or other mental notions) (182).

A fully developed agent-oriented program should have, as proposed by Shoham in (182), three components:

- a logical system for defining the mental state of agents;
- an interpreted programming language for programming agents;
- an *agentification* process, for compiling agent programs into low-level executable systems.

Most research in agent-oriented programming languages is based on declarative approaches, mostly logic based, on the whole appropriate for expressing the high-level abstractions associated with agent systems design (114). In this thesis we have adopted two approaches in order to achieve the agents' reasoning capabilities: an argumentation-based approach *i.e.* based on Dung's argumentation framework (71), and a logic programming semantics *i.e.* Answer Set Programming (ASP). Both of them can be used to specify agent reasoning, such as belief revision and decision-making under uncertainty or complex domains, such the one we are dealing with *i.e.* river basin domain.

In the following sections the basic concepts related to argumentation and ASP in multi-agent decision making context are summarized. Lot of research in the area of Artificial Intelligence (AI) is being done to improve knowledge on these abovementioned systems. Thus, these sections are not intended to be a handbook on argumentation and ASP, only to give the basis to the comprehension of this thesis; the interested reader can refer him/herself to the cited references.

4.4.1 Argumentation theory

Argumentation theory is an interdisciplinary field which attracts attention from philosophers, logicians, linguists, communication studies, among many other areas and applications in both theoretical and practical branches of AI and computer science (56; 124).

In AI a number of approaches to argument and argumentation have been proposed (217). Different senses of argument and argumentation are in use, which leads to a conflation of ideas. Reviews on argumentation theory focus mainly on four principal areas, namely:

1. Formalisms for *argument inference*: in the context of inference, an argument provides reasons to believe in a conclusion. Formally, arguments are built around

a representation language. Different basic forms of arguments can be encountered, depending on the language and on the rules for constructing arguments. Under this area, arguments are defined as inference trees, as sequences of inferences or simply defined as explanation-conclusion (*i.e.* support-claim) pairs (55).

2. *Argumentation-based decision making*: in this context several decision-making problems can be encountered *e.g. decision making under uncertainty*, where the available information about the environment in which the decision takes place is incomplete, imprecise or uncertain; *multiple criteria decision making* whereby each potential choice is evaluated according to different points of view; and *group decision making*, whereby multiple agents have their personal preferences about the collective choice to be made. In all of these situations argumentation can give support and offer techniques to support a more informed decision-making process by means of arguments and counter-arguments for a given situation (8; 9; 18; 145).

3. *Argumentation-based dialogues*: this area of argumentation intends to support or generate interaction between two or more participants, both human or machines. The coherence of a dialogue depends on its goal. Various types of dialogues can be distinguished according to their goals. Walton and Krabbe in (210) present a typology based on the overall goal of a dialogue *i.e.* information-seeking dialogues, inquiry dialogues, negotiation dialogues and deliberation dialogues.

4. *Argumentation-based learning*: this area studies the mutual benefits between argumentation and machine learning, most of them based on case-based reasoning approaches (48; 56).

The interest on using the argumentation theory in MAS research community has recently increased. In MAS domain argumentation-based techniques can naturally be used on one hand, to specify agent reasoning, such as belief revision and decision-making under uncertainty; and on the other hand, to facilitate multi-agent interaction (124). Multi-agent systems depend upon interaction between agents *i.e.* no single agent has sufficient skills or resources to carry out the tasks which the MAS as a whole is faced with. MAS are usually built to operate in the real world, hence the agents must deal with the usual problems of incomplete and uncertain information. Sharing information to reach a common decision is a necessity in MAS. This can be done through dialogue between agents. This dialog can be guided by the use of argumentation, a mechanism which provides a symbolic model for agent decision making (145).

Probably the most outstanding approaches, and the ones we have payed attention, are those of Argument Schemes (AS) from informal logic point of view (209), while much of the more formal work has taken place in the context of abstract Argumentation Frameworks (AF) (71).

In the following two sections the more formal and informal argumentation points of view are briefly described.

Abstract argumentation framework

In this section we provide the basic concepts to illustrate the idea of an *argumentation framework i.e.* how arguments can formally interact, and the *evaluation postulate i.e.* to understand which among the arguments that are in conflict are the winning ones.

Dung's approach (71) is a unifying framework which has played a significant role on argumentation research and AI. The model of argumentation described in (71) is now recognized as providing an important bridge between argumentation theory as a supporting analytic tool for non-monotonic[5] reasoning and the independent exploitation of argumentation models in wider AI contexts and applications (29). The central point of his studies is to work on the *acceptability of the arguments*. This argumentation approach is based on the following four points:

1. Generate **arguments** based on a **knowledge base**: an argument can be described as

   $$< support, claim >$$

   where the support is the reading of the world and the claim its conclusions. For example, the following argument

   $$Arg1 :< a, a \Rightarrow b, b >$$

   concludes b, because from the knowledge base we know that a implies b.

2. See how these arguments **defeat** each other: arguments can be defeated, that is, they can be refuted. This is an important point since it allows the introduction

[5] The term *non-monotonic logic* covers a family of formal frameworks devised to capture and represent defeasible inference, *i.e.* , that kind of inference of everyday life in which reasoners draw conclusions tentatively, reserving the right to retract them in the light of further information. Such inferences are called *non-monotonic* because the set of conclusions warranted on the basis of a given knowledge base does not increase (in fact, it can get smaller) with the size of the knowledge base itself. This is in contrast to classical (first-order) logic, whose inferences, being deductively valid, can never be "undone" by new information (169).

of debate, *i.e.* the possibility to argue for or against a claim. For example, the following argument (Arg2) can be considered an attack to the previous argument (Arg1) since it negates the existence of b.

$$Arg2 :< \{\neg b\}, \neg b >$$

Accordingly, a set of arguments and its relations of attack describe the so called *Argumentation Framework (AF)*, and is represented as

$$AF :=< AR, attacks >$$

where AR is the finite set of arguments and *attacks* is a binary relation on AR. Any AF can be regarded as a direct graph. For example, the graph representation of the following argumentation framework

$$AF :=< \{a, b, b\}, \{(a, b), (b, c)\}$$

is presented in Figure 4.4.

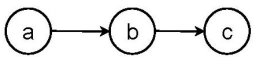


Figure 4.4: Graph representation of AF:=⟨ {a,b,c},{(a,b),(b,c)} ⟩

3. Determine which arguments can be seen as **justified**: notice that the relation *attacks* introduced previously does not tell us which arguments of a discussion can be successful; it only tell us the relation of two conflicting arguments. An important evaluation postulate is as follows:

   An argument is *in* iff all its defeaters are out

   An argument is *out* iff it has a defeater that is in

   To be *in* means to be accepted whereas to be *out* means to be defeated. *Iff* is a logical connective between statements which means that the truth of either one of the statements requires the truth of the other. Thus, either both statements are true, or both are false. Then, in one hand, an AF is called *conflict-free* iff does not contain *a*,*b* such that *a* defeats *b*. On the other hand, an AF *defends* an argument a iff for each argument b that defeats a, AF contains an argument c that defeats b.

After introducing the *attack*, *defend* and *conflict-free* relations, Dung (71) captures the relationships between arguments by defining four abstract argumentation semantics, all of them based on the *acceptable* sets of arguments. An acceptable sets of arguments is called an *extension*. Therefore, an extension can be:

(a) Admissible: iff Args $\subseteq$ F(Args).

(b) Complete: iff Args=F(Args).

(c) Grounded: iff Args is the minimal complete extension.

(d) Preferred: iff Args is a maximal complete extension.

(e) Stable: iff Args is a preferred extension that defeats everything not in it.

where *Args* contains all the arguments in the AF and *F(Args)* are all the defended arguments in the AF.

The admissible extension is accomplished when all the arguments in the AF are conflict free. Intuitively, an admissible set is a coherent point of view. Since an AF can have several coherent points of view, one can take the maximum admissible sets in order to get the maximum coherent point of views. This idea is captured by the concept of *preferred extension*. In the same way, one can take the minimal admissible sets in order to get the minimum coherent points of view. This idea is captured by the concept of *grounded extension*. Finally, the intuitive idea of the *stable extension* is that every stable extension is a preferred extension, but not vice versa.

4. Take the **conclusion** of the justified arguments: that is, to take the acceptable sets of arguments, depending on the semantics (*i.e.* pattern of selection) applied. It is important to remark, from the abovementioned possible extensions, that *any argument is defeated if and only if it is attacked by an acceptable argument.*

In Chapters 6 and 7 Dung's framework will be the basis to evaluate the relation attacks between arguments and the acceptability of them.

Argument schemes and critical questions

Although many of the analyses of arguments are expressed in natural language, there is a tradition of using diagrams to explain the relations between the components of the arguments (29). The aim is to structure these relations simply and graphically in order to promote critical thinking about arguments. *Argument Schemes* (AS) are forms of argument that capture stereotypical (deductive or non-deductive) patterns of reasoning found in everyday discourse (207). This point of view is in line with the aforementioned area of argumentation-based dialogues or, in other words, the use of argumentation for agent communication.

An important, almost defining, characteristic of MAS is that agents need to communicate in order to achieve their individual or collective aims. Hence, an useful aspect of AS is that they each have an associated set of *Critical Questions* (CQ). These CQs help identify various arguments that can be presented in relation to a claim based on the given scheme. Principally, an agent pose a CQ in order to:

- challenge the argument, or to
- attack the argument instantiating a scheme linked to the question (193).

Hence, while an AS can be used to establish a standpoint, the set of CQs help build communication structures about this standpoint.

This approach will be further developed in Chapter 7. Basically, we will develop the idea that agents often have to interact with each other in order to achieve their goals that are subject to a set of constraints (30). In order to do this, special frameworks are needed. We will apply the one presented in (196), focused on a more practical reasoning point of view.

Improving agent communication with argumentation allows agents to exchange arguments, to justify their standpoint and to provide reasons that defend their claims, among other potential benefits (124). Whereas the use of AS together with CQs enables to elicit the relevant arguments and depict the attack-support relations, to resolve these relationships we are going to apply the formal argumentation framework of Dung (71), briefly described in §4.4.1.

4.4.2 Answer set programming

In this section we briefly describe the syntax of the proposed logic programming[6] to codify our domain knowledge: Answer Set Programming (ASP). ASP has been one of

[6]Logic programming is, in its broadest sense, the use of mathematical logic for computer programming. The concept of a stable model, or answer set, is used to define a declarative semantics for logic programs with *negation as failure*. This is one of several standard approaches to the meaning of negation in logic programming, along with program completion and the well-founded semantics. The stable model semantics is the basis of answer set programming.

the most successful logic programming approaches to capture knowledge bases of real domains (22), since it is able capture incomplete information and incomplete knowledge-based states at the same time (136). By using ASP it is possible to represent a computational problem as a logic program whose sets of answers correspond to the solutions of the given problem. Numerous ASP solvers are now available, being the most accepted DLV (69) and SMODELS (184).

Along these lines some basic concepts of logic programming are introduced. An *atom* consists of a word or letter followed by a parenthesized list of constants or variables, affirming or denying something. For example, the atom *problem(bulking)* reports the bulking problem. It is important to know that whereas *constants* express the individual things that exist in the universe of the problem domain and start with lower case, variables are used to generalize things and instead start with a capital letter. Accordingly, the atom introduced previously contains a constant, that is a specific problem $problem(bulking)$, whereas in the atom $wwtp\_operational\_situation(Problem)$ $Problem$ refers to all the problems that can undergo the WWTP.

One of the relevant issues of ASP is that allows to negate the atom using two forms: the negation sign $\neg$ is regarded as the so called *strong negation* by the ASP's literature and the negation *not* as the *negation as failure*. The use of negation as failure is relevant since allows to handle problems with default knowledge, very common in complex domains (22). For example, *not problem(bulking)* reports that the problem of bulking is considered true if we cannot find evidence to support the truth of *problem(bulking)*.

An atom a or the negation of an atom $not\ a$ is called a *literal*. By connecting literals it is possible to form *clauses*. The most used connectives in ASP, as a logic programming language, apart from the abovementioned negation symbols, are $\vee$, $\wedge$, $\leftarrow$ (all of them two-place connectives). The symbol $\vee$ is used to express a disjunction whereas $\wedge$ expresses a conjunction. For example, $A \vee B$ is read as "A or B" and such disjunction is false if both A and B are false. In all other cases it is true. Then, $A \wedge B$ is read as "A and B", and such conjunction is true if A and B are true. In all other cases it is false. The $\leftarrow$ is a converse implication, that is, the literals in the body (right part) imply the ones in the head (left part) of the clause.

A *disjunctive clause* can be expressed as:

$$a_1 \vee \ldots \vee a_m \leftarrow a_1, \ldots, a_j, not\ a_{j+1}, \ldots, not\ a_n$$

where each a_i is an atom, $m \geq 0$ and $n \geq 0$. When $n = 0$ and $m > 0$, the clause is an abbreviation of $a_1 \vee \ldots \vee a_m$. When $m = 0$ the clause is an abbreviation of

$\perp \leftarrow a_1, \ldots, a_n$ such that $\perp$ is the symbol that always evaluates to false. Clauses of this form, that is with the empty head, are used to express *constraints*. The effect of adding a constraint to a program is to eliminate some of its stable models. For instance, the constraint

$$\perp \leftarrow \textit{action(discharge), not wwtp\_operational\_situation(good)}$$

prohibits generating *action(discharge)* if *wwtp_operational_situation(good)* is not generated; that is, adding this constraint eliminates at least one answer.

Therefore, a disjunctive clause C can be expressed in terms of sets of atoms:

$$\mathcal{A} \leftarrow \mathcal{B}^+,\ not\ \mathcal{B}^-$$

where $\mathcal{A}$ contains all the head atoms, $\mathcal{B}^+$ contains all the positive body atoms and $\mathcal{B}^-$ contains all the negative body atoms. A set of clauses of this type is called *disjunctive logic program*.

After briefly introduced the definition of atom, literal, disjunctive clause and logic program, the basis of a possibilistic logic program can be described in the same way. The combination between ASP and possibilistic logic makes possible to capture uncertainties like "it is *probable* that the WWTP overcomes a toxic shock", or "*maybe* the effluent will cause eutrophication to the river".

A *possibilistic atom* is a pair $p = (a, q) \in \mathcal{A} \times Q$, where $\mathcal{A}$ is a finite set and $(Q, \leq)$ is a lattice such that Q is a finite set. Then, a *possibilistic clause* is of the form:

$$r = (\alpha : \mathcal{A} \leftarrow \mathcal{B}^+,\ not\ \mathcal{B}^-)$$

where $\alpha \in Q$. For capturing the uncertainty degrees of the river basin scenario, the set of labels that an expert can suggest are defined by considering Q := {*certain*, *confirmed*, *probable*, *plausible*, *supported*, *open*}. To denote an order relation between these labels the symbol $\preceq$ is used. It denotes a partial order such that the following set of relations holds: $\{open \preceq supported,\ supported \preceq plausible,\ supported \preceq probable,$ $probable \preceq confirmed,\ plausible \preceq confirmed,\ confirmed \preceq certain\}$. Figure 4.5 depicts graphically the previous relations between the used qualifiers. As mentioned before, they are useful to capture degrees of certainty by means of possibilities. Obviously these qualifiers can be properly modified if the context demands it.

Finally, a *possibilistic logic program* is a tuple of the form $\langle (Q, \leq), N \rangle$, where N is a finite set of possibilistic clauses.

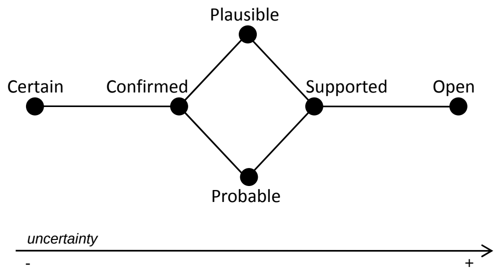


Figure 4.5: Representation of the uncertainty possibilities (Ω lattice)

4.5 Conclusions

The methodology to be developed and used it is based on:

- analyzing the main components of the studied system in terms of agent-based concepts;
- analyzing and describing the general interaction patterns which emerges;
- make special emphasis on knowledge structuring and knowledge inference.

According to the above parameters, an enhanced understanding in each of the following three perspectives of understanding agents is needed. As follows, the three perspectives were reported by Luck *et al.* in (114):

a *Agents as a design metaphor*, when are used to provide ways of structuring an application with autonomous interrelated components. Under this perspective, agents offer a new and often appropriate manner to the development of complex (computational) systems, especially in open and dynamic environments. They lead to the construction of software tools and infrastructure to support the design.

b *Agents as a source of technologies*, covering a range of specific techniques and algorithms for dealing with interactions in dynamic, open environments. Reasoning, deliberation and learning techniques, ways to negotiate and cooperate with other agents, *etc.*, are the issues developed when considering this perspective.

c *Agents as simulation*, offer strong models for representing and simulating complex and dynamic real-world environments, mainly using multi-agent systems. The agent-based simulations provide answers to complex physical or social problems that would be otherwise unobtainable due to the complexity involved.

In this chapter we give an overview of the main concepts for the three perspectives since the application of agents in the urban wastewater system requires all of them, depending on the area or issue we are focusing our attention on (*e.g.* see Table 4.1). For example, for the area of *agent theories* the design metaphor is used whereas for the area of *agent languages* a technological perspective is more convenient.

We have seen that argumentation can serve both as a framework for implementing autonomous agent reasoning (*e.g.* about beliefs and actions) and as a means to structure communication among agents. As a result, argumentation can naturally provide a means for integrating communication with reasoning in a unified framework. This approach will be developed in Chapters 6 and 7.

Chapter 5

Agent-based design of the urban wastewater system

In this chapter a full description of the multi-agent urban wastewater system is given, based on the agent-approach methodology described in the previous Chapter 4. The subsections of this chapter envisage describing a Multi-Agent Urban Wastewater System in order to manage industrial discharges at three specification levels:

- *Level 1: representing the overall system, in order to provide the reusable solutions that can be applied to various kinds of message sequencing that we encounter in the communication among agents.*
- *Level 2: representing interactions among agents, that is, to provide the structural patterns of interactions among agents (graphical layouts emphasizing the chronological sequence of communications as well as the associations among agents).*
- *Level 3: representing internal agent processing in order to specify in detail the process that takes place within an agent in order to implement the protocol.*

Hence, the chapter is divided in three detailed subsections:

- §5.1 corresponding to level 1, that is, to the description of the agents in the system and their associated roles;
- §5.2 corresponding to level 2 and 3, that is, the interaction protocols and the updating of the internal state, respectively. The representation of the internal

state of agents requires a detailed and more concrete specification. Accordingly, from a more reusable solution given in the previous section, inhere a simple but detailed functioning of the agents' internal processing is given. The scale of abstraction is reduced on purpose to show the potential applicability of the proposed multi-agent based solution. And finally,

- §5.3 corresponding to a part of level 2, concretely the associations among agents.

5.1 Agent model: agents and roles in the urban wastewater system

Figure 5.1 shows the possible paths of wastewater flow in the Urban Wastewater System (UWS) depicting the main elements involved in this pathway. The majority of them are considered agents that are in representation of these abovementioned elements (*i.e.* hydraulic infrastructures, treatment facilities, industrial facilities, *etc.*) and accordingly act on behalf of them.

The main agents (understood as pieces of software that encapsulate specific knowledge and special functions) are briefly listed as follows:

Industry Agent (IA) represents individual industries and/or groups of industries that, as a result of their production process, need to manage their produced wastewater. They can discharge wastewater into the sewer system, into WWTP through a tanker or directly to the receiving media (if properly treated within the particular facility). The most frequent action performed by IA is to manage the industrial wastewater that is discharged into the sewer system where it is collected together with other inflows and transported to the WWTP.

Industrial Tank Agent (ITA) represents the infrastructure available to store industrial wastewater, with the function to contain and laminate wastewater towards the sewer net. Each available industrial tank is represented by an agent.

Household Agent (HA) represents a simple information carrying agent that supplies the domestic wastewater discharge data (domestic wastewater production).

Sewer Agent (SA) represents the sewer infrastructure that is mainly responsible of collecting and distributing wastewater (domestic and industrial), together with the collected rainfall, to the WWTP.

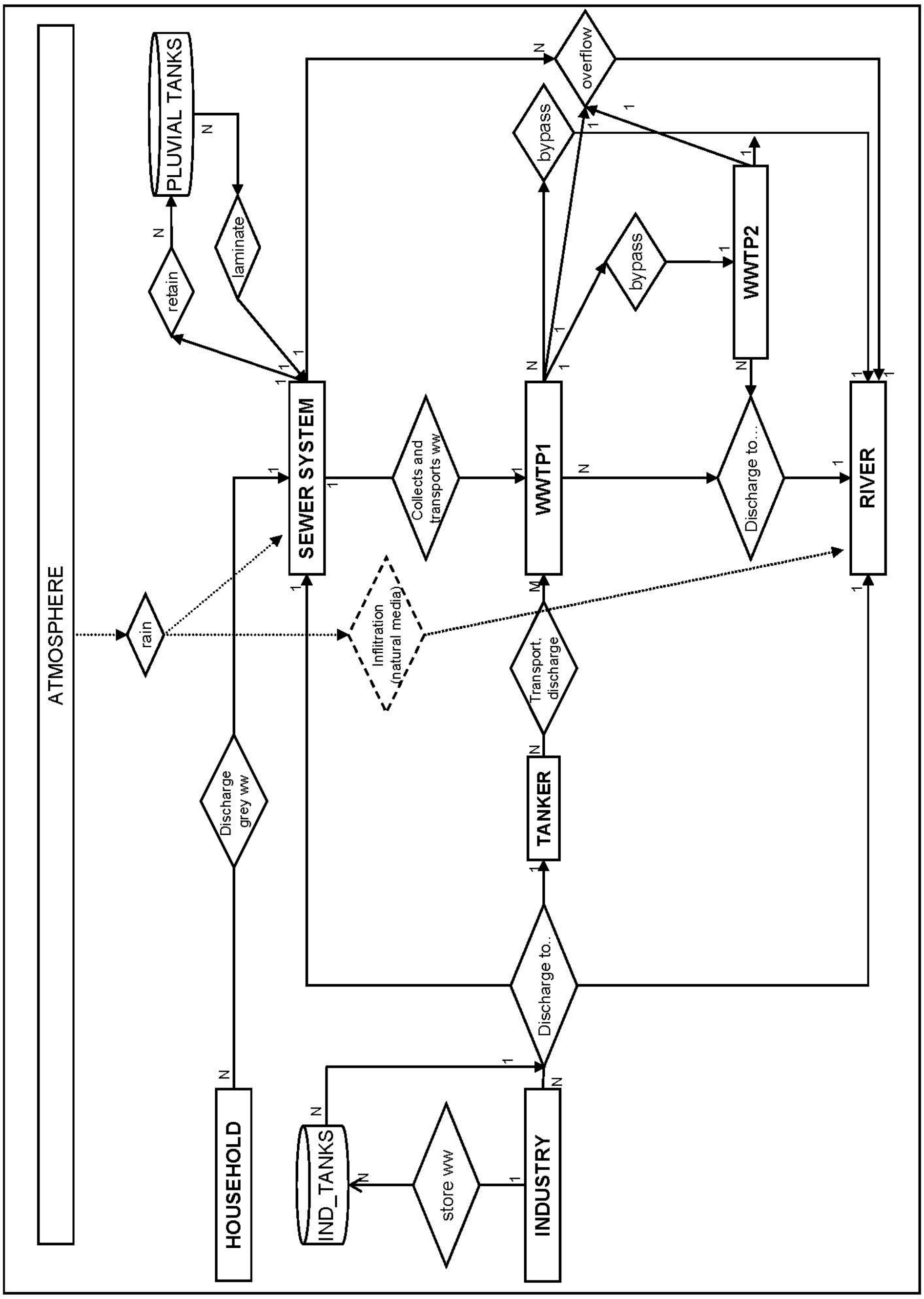


Figure 5.1: Wastewater flow diagram (compartments and processes included in the studied system)

Sewer Tank Agent (STA) represents the infrastructure available to store wastewater (mainly when rainfall events occur) within the sewer system, and regulate its discharge to the sewer.

Wastewater Treatment Agent (WTA) represents the WWTP receiving wastewater discharges from several sources (*i.e.* households, industries -individual or industrial tanks-, *etc.*) and treating the wastewater to be discharged into the receiving media (generally the river).

Bypass Agent (ByA) represents bypass channel state and regulates bypass gates, so its main function it is to manage bypasses (transporting wastewater from one WWTP to another just before or after the primary treatment).

River Protection Agent (RPA) represents river conditions, so this agent supplies the system with the current water quality as well as the Water Quality Objectives (WQO) to be achieved into the river.

Meteorologist Agent (MA) represents weather conditions and holds data from rainfalls events when occurring (intensity and duration of the event).

Administrator Agent (AA) represents the authority that put taxes and charges to the emitting agents (*e.g.* IA, ITA, STA and WTA) in the UWS. Its main function is to calculate wastewater discharge costs.

The brief description of all these agents shows the idea of the agents doing tasks. These tasks are further described by means of roles. These roles will be then distributed over the range of agents in order to perform specific tasks to achieve specific purposes. Normally each agent status involves not a single associated role, but an array of roles to accomplish its goal (see Figure 5.2).

For each role in the system we have fill in a GAIA role schema (see Tables 5.1–5.10).

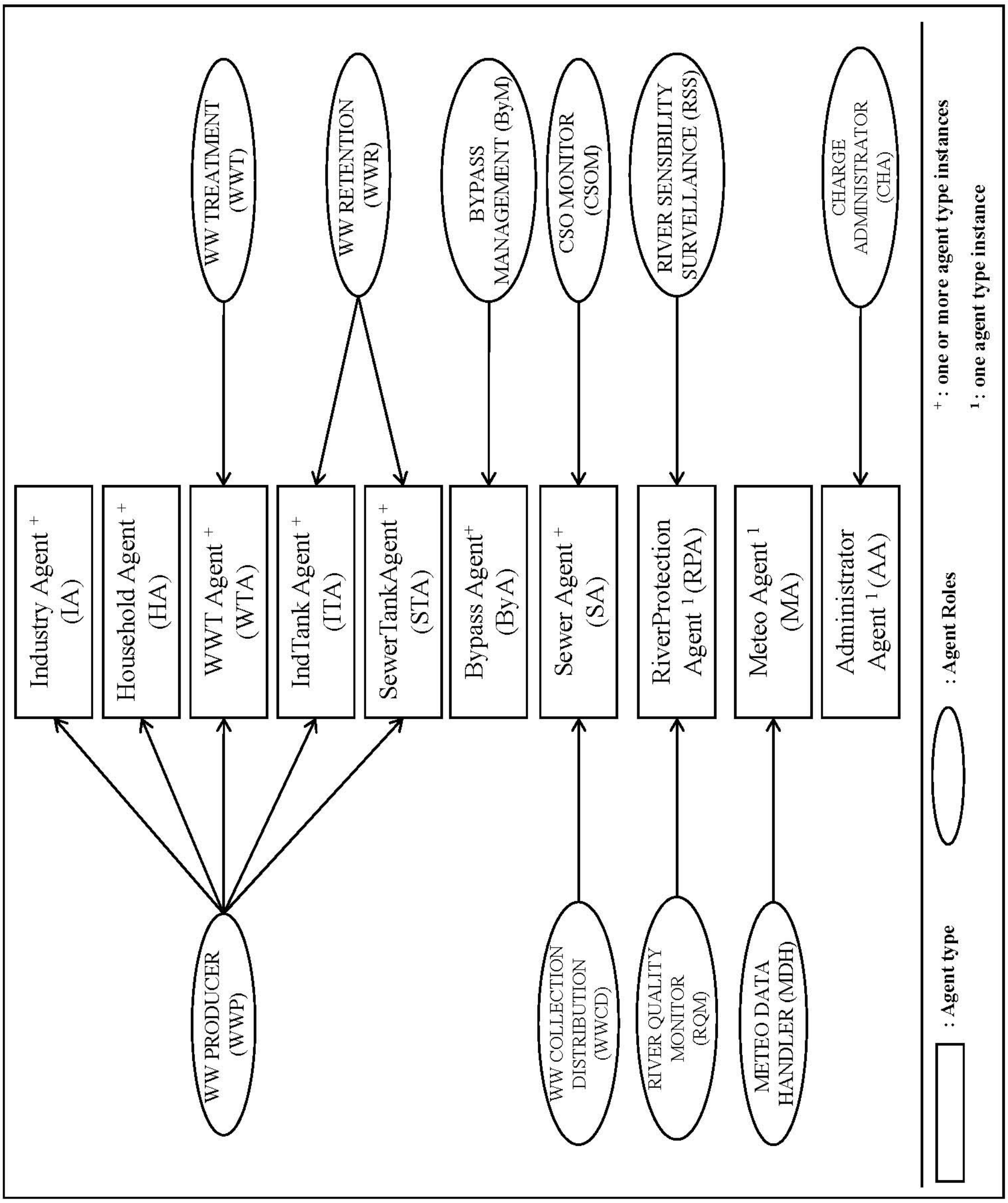


Figure 5.2: Agent model

Table 5.1: Schema for the WasteWater Producer role

Role	WasteWaterProducer (WWP)
Description:	Simulates the behaviour of an individual producer, quantity and quality of wastewater produced as a consequence of its activity. Informs the receiver of the discharge about it.
Protocols & Activities:	CheckFlow, CheckPollutants, CheckToxicity, ProduceWastewater, ProposeDischarge, InformDischargeCharacteristics, QueryDischargePrice
Permissions:	Reads: chemical sensors, flow meters, toxicity indicators, analytical tests Reads: production model Writes: individual (private) production Creates discharge plans
Responsibilities	
Liveness:	WWP = (CheckFlow.CheckPollutants.CheckToxicity)$^{\infty}$ ǁ ProposeDischarge . InformDischargeCharacteristics . QueryDischargeCost
Safety:	Readings ∈ LegalTresholds

Table 5.2: Schema for the WasteWater Treatment role

Role	WasteWaterTreatment (WWT)
Description:	Keeps track of wastewater flow that arrives at WWTP (computes the total inflow and load of polluting substances); supervise and control the treatment process, informing about the WWTP state if asked and giving alarms when a problem occurs; manages WWTP control setpoints; calculates operation yields, treatment costs and gives the final quality of the treated wastewater.
Protocols & Activities:	QueryInflowCharacteristics, TreatWastewater, SuperviseControl (atl), InformState, OperateSetPoints, InformEffluentQuality, CalculateTreatmentCost, InformTreatmentCost, ProposeBypass
Permissions:	Reads: treatment model, hydraulic capacity, treatment capacity, wastewater productions. Writes: total inflow, total outflow, quality of treated effluent, WWTP state, alarms, cost. Executes: control commands
Responsibilities	
Liveness:	WWT = QueryInflowCharacteristics. TreatWastewater . SuperviseControl . InformState* . OperateSetPoints*. InformEffluentQuality . CalculateTreatmentCost . InformTreatmentCost . ProposeBypass
Safety:	Total Inflow $\leq$ Hydraulic capacity EffluentQuality $\in$ Directive 91/271/EEC

Table 5.3: Schema for the Wastewater Collection and Distribution role

Role	Wastewater Collection and Distribution (WWCD)
Description:	Collects and distributes wastewater coming from the different sources. Processes data gathered from sewer sensors and entering discharges. Inform about failures, breakdowns, corrosivity, *etc.*
Protocols & Activities:	CheckSewerSensors, DiagnoseSewerState,Query DischargeCharacteristics, CalculateTotalDischarges, InformSewerState
Permissions:	Reads: sewer sensors, sewer model Writes: diagnosis
Responsibilities	
Liveness:	WWCD = $\underline{\text{CheckSewerSensors}}^{\infty}$. $\underline{\text{DiagnoseSewerState}^{*}}$. QueryDischargeCharacteristics . CalculateTotal Discharges . InformSewerState
Safety:	Limits of sewers (quantity and quality); Quantity limits < capacity limits of sewer Pollution limits < safety ones (according to the materials of sewer, *etc.*)

Table 5.4: Schema for the Wastewater Retention role

Role	Wastewater Retention (WWR)
Description:	Manages the retention/lamination actuators from storing tanks (*i.e.* industrial, sewer). Keeps track of industrial tanks and sewer tanks availability as well as their status (processes and problems that might occur depending on the characteristics of retained wastewater) and informs about it. Calculates storing costs.
Protocols & Activities:	ReceiveDischargeProposals, QueryDischarge Characteristics, CalculateTankInflow, CalculateTankLoad, DiagnoseTankState, InformTankState, OperateTankGates, CalculateStoreCost
Permissions:	Reads: level sensor, discharge proposals, tank model Writes: status of the tanks, capacity Executes: open/close gates
Responsibilities	
Liveness:	WWR = ReceiveDischargeProposals . QueryDischarge Characteristics . CalculateTankInflow ‖ CalculateTank Load .(DiagnoseTankState* ‖ InformTankState*) . OperateTankGates* . CalculateStoreCost
Safety:	TankLevel ≤ 95% maximum capacity

Table 5.5: Schema for the Bypass Management role

Role	Bypass Management (ByM)
Description:	Controls bypasses by opening or closing the gates. Keeps track of the bypass channel state and inform if a problem arises.
Protocols & Activities:	OperateGates, CheckChannelState, InformBypassState, ReceiveByPassProposal
Permissions:	Reads: flow sensor Executes: open/close gates
Responsibilities	
Liveness:	ByM = ReceiveByPassProposal . CheckChannelState* . InformBypassState*. OperateGates*
Safety:	Flow < maximum capacity Pollution Limits < safety ones for the channel

Table 5.6: Schema for the Combined Sewer Overflow monitor role

Role	CSO Monitor (CSOM)
Description:	Keeps track of all Combined Sewer Overflows that occur into the system, their characteristics (quantity and quality) and localization. Evaluates the impact on the receiving media and informs about it.
Protocols & Activities:	MonitorCSO, EvaluateCSOImpact, InformCSOImpact
Permissions:	Read: flow sensors; analytical measures Write: impact risk of CSO
Responsibilities	
Liveness:	CSOM = MonitorCSO$^{\infty}$. EvaluateCSOImpact* . InformCSOImpact*
Safety:	Risk of CSO < goal (*e.g.* 20 mg COD/l) (3)

Table 5.7: Schema for the River Sensitivity Surveillance role

Role	River Sensitivity Surveillance (RSS)
Description:	Surveys the sensitivity of the river that depends on the intended water uses at each part of the river (fish life, irrigation, bathing area, leisure uses, shellfish production, supply, *etc.*) and the sensibility on the area (protected, nitrates vulnerability, aquifers, *etc.*). It collects the information coming from the different social groups involved in the river basin (NGO's, neighborhood communities, fishing associations, individuals, *etc.*) that want to express their opinion and interests.
Protocols & Activities:	CheckSensitivity, InformSensitivity, ReceiveRequests
Permissions:	Reads: river sensitivity
Responsibilities	
Liveness:	RSS = CheckSensitivity^{+} . InformSensitivity* . ReceiveRequests*
Safety:	Special requirements for sensible areas

Table 5.8: Schema for the River Quality Monitor role

Role	RiverQualityMonitor (RQM)
Description:	Updates the status of the river (according to the incoming discharges and the river quality model) and informs about it.
Protocols & Activities:	CheckRiverQualityParameters, CalculateRiverState, QueryDischargeCharacteristics, QueryMeteoData, InformRiverState
Permissions:	Reads: river quality model, values from river quality stations Writes: state of river
Responsibilities	
Liveness:	RQM = CheckRiverQualityParameters$^{\infty}$. CalculateRiver State. QueryDischargeCharacteristics . QueryMeteoData . InformRiverState
Safety:	RiverQuality $\in$ quality goals DilutionCapacity = $\frac{DischargedFlow(annualaverage)}{RMFlow(maintenanceflow)} < 50$ %

Table 5.9: Schema for the Meteorological Data Handler role

Role	MeteorologicalDataHandler (MDH)
Description:	Supply the system with meteorological conditions (temperature and rainfall data).
Protocols & Activities:	CheckMeteoEvents, InformMeteoEvents
Permissions:	Reads on-line meteorological data
Responsibilities	
Liveness:	MDH = CheckMeteoEvents* . InformMeteoEvents*
Safety:	A successful connection with the on-line meteorological database.

Table 5.10: Schema for the Charge Administrator role

Role	Charge Administrator (CHA)
Description:	Manages Economic Instruments aimed to punish, sanction or encourage the producers to reduce their polluting discharges. Asks all wastewater producers for their wastewater production in order to calculate emission costs for each discharge proposal.
Protocols & Activities:	QueryDischargeCharacteristics, ApplyEconometricModels, QueryTreatmentCost, QuerySensitivity, SendPrices, UpdateSanctionList
Permissions:	Reads: econometric model Writes: prices
Responsibilities	
Liveness:	CHA = QueryDischargeCharacteristics . QueryTreatment Cost . QuerySensitivity . ApplyEconometricModel . SendPrice . UpdateSanctionList
Safety:	True

Once all the roles of the system are described they can be distributed among the agents in order to give them specific task(s). The Agent Model presented in Figure 5.2 depicts the relation between agents and roles giving the instances of each agent type for each role. The agent model informs about which agent perform each role. The agent type instances depicted with a (+) or (1) give information about how many types of agents can exist: one or more agent type instances or only one, respectively (see §4.3.1 for the general definition). Thus, the *wastewater management scenario* proposed is represented by one Administrator Agent, one Meteorological Agent and one River Protection Agent, but by multiple individual agents representing each one of industries, communities, wastewater treatment plants and so on present at the river basin scale.

5.2 Interaction model

At this stage, we are going to further develop the services, that is to say, the functions of the agents. They can be obtained from the list of protocols, activities, responsibilities and liveness properties of roles described in Tables 5.1 to 5.10.

Tables 5.11–5.12 portray the service model. Take notice that for each service there is a protocol described in terms of the following attributes:

- *initiator*: the role(s) responsible for starting the interaction,
- *partner*: the responder role(s) with which the initiator interacts,
- *inputs*: the information used by the initiator role while performing the protocol and,
- *outputs*: the information supplied by the protocol responder during interaction.

The activities (which are underlined in Tables 5.1–5.10), although they are services supplied by specific agents, they are not represented in the service model as they are tasks than an agent can do without interacting with other agents. For this reason we provide the principal information used to define the activities (*e.g.* CheckFlow, CheckPollutants, CheckToxicity, *etc.*) in Tables 5.13–5.14, specifying the inputs and outputs of each activity. Moreover, several of the activities' inputs are models and equations used by the agent to perform tasks and to update their internal state. Hence, in §5.2.1 those activities related to the updating of agent's internal state are detailed.

Table 5.11: Service Model for the wastewater management system

SERVICE	INITIATOR	PARTNER	INPUT	OUTPUT
ProposeDischarge	WWP	WWCD, WWR	Propose discharge action	Acceptance or rejection of the proposed action
QueryDischarge Characteristics	WWR WWCD, RQM,CHA	WWP	Ask discharge characteristics	Receive values of discharge characteristics parameters
QueryInflow Characteristics	WWP	WWCD, WWT, WWR,RQM, CHA	Ask quality and quantity of inflow wastewater	Receive values of flow and quality of wastewater (result of CalculateTotal Discharge activity)
InformDischarge Characteristics	WWP	WWCD, WWT, WWR,RQM CHA	Results of CheckFlow, CheckPollutants and CheckToxicity activities	Receive discharge characteristics: values of Flow, Pollutants and Toxicity
QueryDischarge Price	WWP	CHA	A question (*how much?*)	Price (€or €/m^3)
InformState	WWT	WWP	Results of ATL[1] data acquisition and management modules	State of the plant (operational problems)
InformEffluent Quality	WWT	RQM	Characteristics of treated wastewater (COD, BOD, TSS, nutrients)	Receive effluent quality values
InformTreatment Cost	WWT	CHA	Cost of treatment (according to inflow wastewater characteristics)	Receive treatment cost
InformSewerState	WWCD	WWP	Results of CheckSensors and DiagnoseSewerState	Receive Sewer State
InformTankState	WWR	WWP WWCD	Results of DiganoseTankState activity: current capacity, corrosivity, leakage, formation of toxic substances, *etc.*	Receive tank state

[1]ATL stands for the WWTP supervisory and control system (see §5.2.1). It is structured in four modules: data acquisition, knowledge management, control and simulation *i.e.* expert system.

Table 5.12: (continued) Service Model for the wastewater management system

SERVICE	INITIATOR	PARTNER	INPUT	OUTPUT
ProposeBypass	WWT(1)	WWT(2)	A question (*can I?*)	Acceptance or rejection of the proposed action
RequestBypass	WWT	ByM	Send a request for a bypass	Acceptance or rejection of the proposed action
InformBypass State	ByM	WWT(1)	Results of CheckBypassChannel activity (state of bypass channel: current capacity, *etc.*)	Receive tank state
InformCSO Impact	CSOM	RQM	Results of Monitor and EvaluateCSOImpact activities	Value for impact risk of CSO (CSO_IR)
InformSensitivity	RSS	CHA	Results of CheckSensitivity activity	Receive kind of sensitivity
InformRiverState	RQM	AA, WWP	Results of CalculateRiverState activity	Receive river state
QueryMeteo Events	RQM, WWCD	MDH	A question	Values of intensity and duration of the event
InformMeto Events	MDH	RQM, WWCD	Results of CheckMeteoEvents	Receive meteo data
QueryTreatment Cost	CHA	WWT	A question (*how much?*)	Cost, €
SendPrice	CHA	WWP	Results of Apply EconometricModel	Receive cost of environmental charges

Table 5.13: Description of activities (tasks an agent do without interacting)

Activity	**INPUT**	**OUTPUT**
CheckFlow *(WWP)*	On-line flow sensors Wastewater Production Models	Wastewater flow rates (m^3/hour)
CheckPollutants *(WWP)*	On-line data, off-line data (from tests) Wastewater Production Models	Values for at least the next parameters: BOD,COD,TSS,TN,TP,KjN, $N\_NH_4{}^+$, Temperature, pH
CheckToxicity *(WWP)*	Toxic tests	Values for equitox and/or specific pollutants
TreatWastetwater *(WWT)*	WWTP model	Effluent characteristics (BOD, COD, TSS, Nutrients) (g/m^3)
SuperviseControl *(WWT)*	ATL expert system	Predict operational problems (bulking, foaming, deflocculation, rising, *etc.*)
OperateSetPoints *(WWT)*	ATL control module	Change setpoint (DO,Q_{RAS}, $Q_{WAS\text{-}Primary}$, $Q_{WAS\text{-}Secondary}$)
CalculateTreatment Cost *(WWT)*	WWTP operation and maintenance cost equations	Cost (€/m^3) and total cost (€)
CheckSewerSensors *(WWCD)*	Measurement chambers (sensors) Sewer model (balance of arriving wastewaters)	Values for (Flow, Pollutants, Toxicity) characteristics of wastewater inside the sewer system
DiagnoseSewerState *(WWCD)*	Sewer model Operators (protocols of operation and maintenance)	Sewer System Problems: - corrosivity of materials - pressure (hydraulic capacity overpass) - bad design of pipes, connection, construction, *etc.*
CalculateTotal Discharges *(WWCD)*	Inflow equation mass balance	Values of flow rate and concentration of discharged substances
CalculateTankInflow *(WWR)*	Tank inflow equation	Total inflow (m^3/hour)
CalculateTankLoad *(WWR)*	Tank load equation	loads of BOD, COD, TSS, nutrients, ammonia (Kg)
DiagnoseTankState *(WWR)*	Tank equation Tank model	Current state (capacity and matter balance) of the tank at each moment
OperateTankGates *(WWR)*	ATL control module	Action of opening or closing gates
CalculateStoreCost	Storing cost model or equation	Cost (€/m^3) and total cost (€)
CheckChannelState *(ByM)*	Received message about wastewater characteristics that are going to be bypassed. Bypass channel sensors Model for the channel	State of the channel (possible problems, capacity)

Table 5.14: (continued) Description of activities (tasks an agent do without interacting)

Activity	**INPUT**	**OUTPUT**
MonitorCSO *(CSOM)*	Sensors at sewer tanks	Values for flow, pollutants, and toxicity characteristics
EvaluateCSOImpact *(CSOM)*	CSO_RI equation	Value for impact risk of CSO
CheckSensitivity *(RSS)*	River data base	Level of sensitivity: aquifer, protected area, nitrates vulnerability, water use, reservoir
CheckRiverQuality Parameters (*RQM*)	Flow meter (flow gauges) Quality measurement stations	Upstream values for river water quality: COD, BOD, TSS, pH, T
CalculateRiverState *(RQM)*	River model	Downstream values for river water quality
CheckMeteoEvents *(MDH)*	Meteorological gauges	Intensity and duration of rainfall Quantity of rainfall (m^3) Environmental temperature
ApplyEconometricModel *(CHA)*	Econometric model Economic instruments	Price (€/m^3 or total €)
UpdateSactionList *(CHA)*	Sanction rules	List of sanctioned wastewater producers

As shown in Table 5.11–5.12, the performance of services requires interaction and communication between two or more agents The communication is the ability to exchange information by means of sending-receiving messages (*e.g.* WWP sends a message informing the discharge characteristics and at his turn WWT receives the message). Therefore, the act of communication between agents is in one part, the capacity of receiving messages (*perception*) and, in another part, the capacity of sending messages (*action*). The content of the messages interchanged for the wastewater management in the UWS is fully described in §5.2.2.

5.2.1 Updating of agent internal state

In this section a description of the internal state and the models that updates the internal state of each agent in the Multi-Agent Urban Wastewater System is described. The internal state depends on the percept history and in that way reflects at least some of the unobserved aspects of the current state (*e.g.* keeping track of the part of the world it can not see now) (169). Updating the internal state as time goes by requires two kinds of knowledge to be encoded in the agent program:

- Information about *how* the world evolves independently of the agent.
- Information about *how* the agent's own actions affect the world.

Agents that use models to update their internal states are often called model-based agents. The aim of all agent updating models is to show how the current percept is combined with the old internal state to generate the updated description of the current state. Most of them make use of the available information about how the world evolves in order to interpret the new percept in the light of existing knowledge about the agent internal state.

Sato and Hashimoto in (174) propose a simple model representing the agent having internal dynamics. Their idea is to show how agents have internal states that do not only change with external stimuli returning some responses. Instead, the internal state of agents (like humans) change autonomously since agents often do show various behaviours in the same situation (known as *diversity*). However, the sequence of behaviours is usually not completely random, but has a certain causality (this property is called *consistency*). The autonomous change of the internal state is known as the internal dynamics and its formalization is by means of Equation 5.1:

$$a(t) = B(x(t)) \tag{5.1}$$

where
a(t) is the agent's action at time t;
x(t) is the internal state of the agent at time t and
B is a function to decide how the agent behaves when has certain internal state. Since the internal state changes autonomously its dynamics is represented by means of Equation 5.2:

$$x(t) = I(x(t-1), a(t-1), s(t)) \quad (5.2)$$

where the first term represents the past internal states, the second the agent's past actions and the last the present external stimulus. Equation 5.2 is represented in Figure 5.3 for a better understanding.

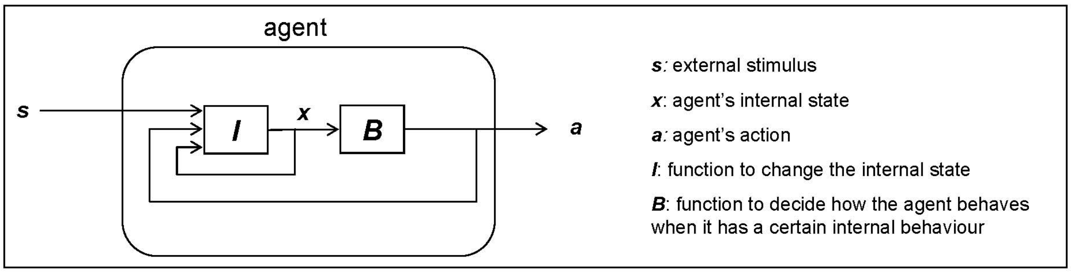


Figure 5.3: Schematic view of an agent having internal dynamics

Accordingly, in this section we describe the most relevant functions/models considered in order to update the internal state for each agent in the system, as well as the functions and/or rules that model the agent's behaviour. Both of them influence the agents' actions in the MAS. It is important to say that, since the objective of this work is not to go into the models, this is only a brief review of a possible updating and behavioural model for each agent, among others. For the internal state we will summarized the most modelled components (*i.e.* sewer, WWTP and river) and make a simple proposal for the rest. For the inter-agent behavioural decision modules of some agents we will depict a proposal within a separately Box (just to exemplify the requirement of having this level when using an agent-based modelling approach).

Wastewater production agent models

Household Agent: the *IWA Task Group on Benchmarking of Control Strategies for WWTPs*[7] provides a standard dynamic profile for domestic wastewater production (in terms of flow and some pollutants). Daily and weekly typical profiles describing a normal behaviour for domestic wastewater arriving at WWTPs are depicted in Figure 5.4. The profiles hereby presented are the ones corresponding to 'dry weather'. This means much lower peak flows at the early morning since at night water consumption is lower (basically, the wastewater is from infiltrations and from little quantities of sanitary water). The first peak is, generally, immediately after the maximum use of water in the morning. A second peak is normally at the last hours in the afternoon, between 19:00 and 21:00 (more variable according to the length of the sewer and the population) (189). For weekly variations the most important observation is that during the weekend there is a little reduction on the consumption of water, hence on the production of wastewater.

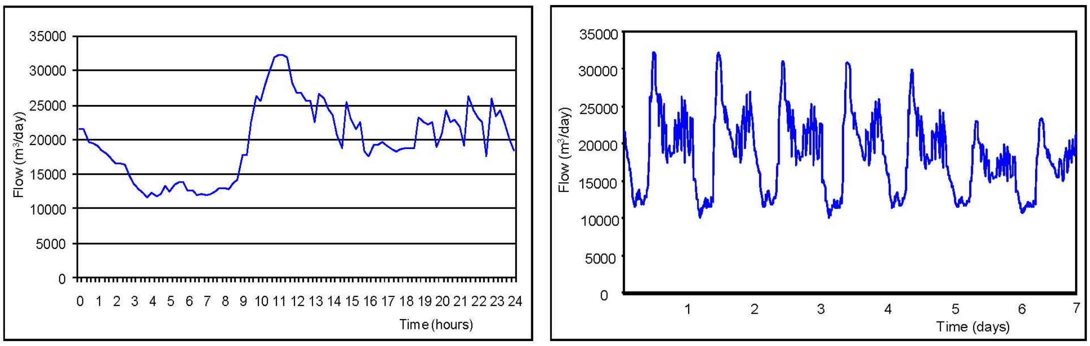


Figure 5.4: Daily (left) and weekly (right) domestic wastewater production profiles

Industries' Agents: obviously the wastewater production profiles are totally dependent on the type of industry. As an example, four types of industries could be considered with the following production profiles:

1. Pharmaceutical Industry: it has a weekly planning (starting on Monday and closing during the weekend) consisting on three units of production; the first unit lasts for 24 hours, the second occurs during the next 48 hours, and finally a third

[7] The data files are downloadable at:
http://www.ensic.inpl-nancy.fr/benchmarkWWTP/Bsm1/Benchmark1.htm#Ancre05

during the next 48 hours. The production of wastewater increase during the week according each production unit (from 200 m^3/day to 1000 m^3/day).

2. Paper Industry: it has a constant production during all week (average of 5000 m^3/day), thus we assume the discharge does not vary, unless an emergency or a change in the production plan occurs.

3. Slaughter Industry: it works continuously and produces two peaks of wastewater (one in the morning and another one in the afternoon) according to the finishing of the main activities (*i.e.* slaughtering and quartering).

4. Textile Industry: it has three daily turns and produces during all the week. During the second turn the production of wastewater is increased, while during the first and the third it is approximately the same.

In the same way, simple models for the secondary producers (*i.e.* industrial tanks, sewer tanks and WWTPs) can be used. We name secondary producers the ones that receive at some point wastewater from a primary producer (*e.g.* households and industries) and return it to the system later on (with the same or different characteristics depending on the importance of transformation processes).

An example of how Industry Agents could make decision is depicted in Box 5.1.

Industrial Tank Agent: its behaviour depends on its available capacity at each time. As depicted in Equation 5.2, the agents' internal state dynamics is a function of the past internal states (*x(t-1)*), the past actions (*a(t-1)*) and the present external stimulus (*s(t)*). Thus, the capacity of the tank can be expressed as a rate (see Equation 5.3), and *s(t)* of Equation 5.2 can be represented by the Inflows (incoming discharges), *x(t-1)* is the *InitialState* (the volume occupied at time t-1) and *a(t-1)* is the industrial tank agent's action to discharge its content to the sewer in order to prevent the tank to overflow or break.

$$Capacity(t, h) = (Inflow - Outflow) * time(t, h) + InitialState \tag{5.3}$$

We assume homogeneity and no transformation of the substances inside the tank (non-reactive vessel), and the balance of the concentration C of one substance in the tanks is a mass balance describe in Equation 5.4.

$$C = \frac{\sum_{i=1}^{n} Q_i \cdot C_i}{\sum Q_i} \tag{5.4}$$

Box 5.1. Simple rules representing Industry Agent decisions when dealing with their wastewater discharges can be defined, for instance, under some economical criteria, such as:

- *Firstly, the principal desire of each IA is to spend the less possible resources when dealing with its wastewater discharges. Accordingly, it will decide to discharge where less costly.*
- *Given an affirmative answer from its discharge-request and the different costs of discharge, it will compare the cost of discharging to a WWTP with the one at Industrial Tank. If the current cost of discharging to a WWTP is less than the cost of storing into industrial tanks, then the IA will decide to discharge into the WWTP. Otherwise, and if there is enough capacity, it will discharge to industrial tanks.*

In the worst case, given a proposal-rejection for both, the WWTP and the Tank, the industry should have to discharge directly into the river (see Figure 5.5). This action is the worst possible solution in the overall UWS and RPA will highly penalized this action to compensate ecological damage. Hence, either compensation or punishment, can be given to industries according to their inter-agent behaviour and the pollution contribution to the system.

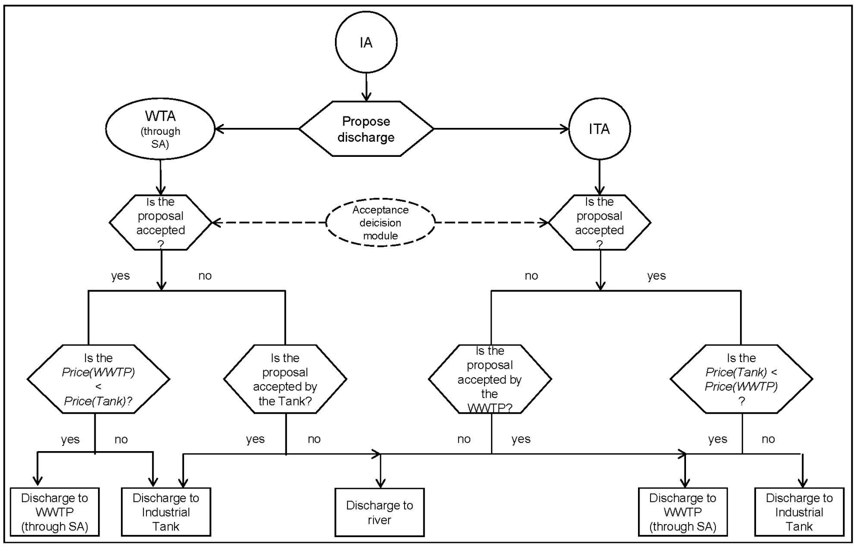


Figure 5.5: Industry's decision module

where:

n = number of total industrial discharges into the tank;

Q_i= inflows (discharged flow of industry i);

C_i= concentration of substance i contained in the discharge.

Box 5.2. Industrial Tank Agents could follow a set of rules of the following type in order to accept industrial discharges. As follows:

- ITA does not accept an industrial discharge if Capacity (t, h) > 95 % (capacity is updated according to Equation 5.3)
- Priority of discharge acceptance is according to the following criteria:
  1. *Connection.* Discharges coming from directly connected industries.
  2. *Discharging history.* Prioritize those industries with less negative punctuation in their discharging history.
  3. *Number of discharges into the tanks.* Prioritize those industries with less number of discharges into the tank during the last 48 hours.

It is necessary as well to define how each agent behaves when it has a certain internal state (Figure 5.3, function B). Accordingly, ITA's decision module to empty the tank could be simple rules *w.r.t* its volume and capacity.

Sewer tank agent: possible sewer system overflows can occur; sewer tanks are used widely for regulating pollution caused by CSO. Lessard and Beck in (111) propose four modes of behaviour for dynamic simulation of sewer tanks *i.e. fill* –when the tank is filling during an event–, *dynamic sedimentation* –when the tank is full and overflowing to the receiving body–, *quiescent settling* –when the tank is partly or completely full and no flow is entering or leaving the basin– and *draw* –corresponds to the pumping of the sewer tank contents from the basin back to the plant stream–.

As a management criteria the impact risk of CSOs to the receiving media is often evaluated in terms of some evaluation index. For instance the Water Catalan Agency in (3) propose to evaluate it by using the following Equation 5.5 (see §2.2.2):

$$CSO\_RI = \frac{1}{20} \times \frac{V_{runoff} \times COD}{Q_{RN}} \tag{5.5}$$

where:
CSO_RI is the risk of combined sewer overflows;
V_{runoff} = rain × A_u × C_{imp} where *Vrunoff* is the volume that overflows and,
rain is the annual precipitation;
A_u is the urban area associated to each CSO;
COD is the recommended concentration in mg/l;
Q_{RN} is the natural flow rate;

C_{imp} is a waterproof ('impermeabilization') coefficient.

If it is assumed that all CSOs arrive at the same point (taking into account a little sub-catchment of the river basin), it will be necessary to recalculate concentrations and flows for this specific point at each simulation time. Equation 5.6 shows how the concentration can be obtained:

$$C_p = \frac{\sum_{i=1}^{n} Q_i \cdot C_i}{Q_t} \tag{5.6}$$

where:
C_p = concentration of a quality parameter of the CSO discharge;
n = number of total CSO;
Q_i = flow of CSO;
C_i= concentration of CSO and
Q_t = total flow for the n CSO

An example of how STA could make their own decisions is depicted in Box 5.2.

Sewer agent model

For the hydraulics behaviour the most used models are based on *Saint-Venant* equations (49). The main consideration of these equations is the mass and momentum conservation within a constant (channel) section. For the water quality processes within the sewer system the following processes are usually considered (163):

- pollutants surface accumulation and wash-off,
- transport in sewers (including sedimentation and re-suspension),
- conversion processes (from considering no conversions to consider the sewer system as a physical, chemical and biological reactor).

Most applications make use of surrogate models (70; 125; 203) taken from the most complex mechanistic ones (11; 61). For a very simple approximation it can be only considered the flow and pollutant transport in sewers and sewer tanks. The pollutants can be assumed to be completely mixed in the system without any biochemical transformation. The main pollutants simulated in the sewer system are suspended solids, volatile suspended solids, total chemical oxygen demand, soluble chemical oxygen demand, ammonium and nitrate. A simple mass balance can be used by the sewer agent to update the pollutants concentration arriving into the sewer, and then transmitted to the WWTP. There is no interaction between polluting substances and between them with the environment. Hence, the concentration of dissolved pollutants and of suspended solids in the pipes can be calculated as shown in Equation 5.4.

Bypass agent model

The behaviour of a bypass agent is equivalent to the behaviour of a sewer agent. The most applied simplification is to consider only the flow and pollutant transport in the bypass channel(s). As in the sewer, the pollutants can be assumed to be completely mixed in the system without any biochemical transformation.

A simple mass balance can be used by the bypass agent to update the pollutants concentration arriving into the bypass channel, and then transmitted to another WWTP. There is no interaction between polluting substances and between them with the environment. Hence, the concentration of dissolved pollutants and of total suspended solids in the channel can be calculated as shown in Equation 5.4.

Wastewater treatment agent model

The WWTP internal behaviour is mainly modelled using unit processes *e.g.* clarifier's unit and reactor's (activated sludge) unit. These processes have been mathematically described and the most widely applied are those described by Tackács *et al.* (187) and Henze *et al.* (90), for clarifiers and (activated sludge) reactors respectively. These models have become a standard and several software packages are available to deal with their computation.

These models have been shown to adequately describe the behaviour of nitrogen and biological and chemical phosphorous removal processes, more particularly in terms of the oxygen demand, sludge production and nitorgen/phosphate removal (163). The intended function of a WWTP agent model is to estimate costs and removal efficiencies for a WWTP operated by an activated sludge system configuration (see Figure 2.2). This is a significant task, requiring specialists in wastewater engineering, in order to manage the complex models of the activated sludge system on the basis of the several possible alternatives and optimization criteria (78; 79; 200).

It is important to mention that an agent-based application to manage WWTP's unit processes was released by Sànchez-Marrè *et al.* in (172) and has been developed under the name of ATL (168; 173) (see §3.1). Taking into account that this system can be applied to each WWTP, it might result very useful when updating the internal state of the wastewater treatment agents.

River agent model

Changes in water quality of rivers are due to physical transport and exchange processes (such as advection and diffusion/dispersion) and biological, biochemical or physical conversion processes (163). The extended Streeter-Pehlps formulation is one of the simplest, but most widely used, water-quality river behavioural model (102). The model is static, *i.e.* it assumes that both flows and emissions are steady. The approach also assumes that advection (*i.e.* the movement of pollutants downstream) is the only form of pollutant transport and that dispersion through turbulent mixing is not significant. Finally, complete mixing is also assumed. To overcome the several shortcomings of this model, the IWA Group on River Water Quality Modelling was create to set the technical basis from which to formulate standardized, consistent river water quality models (164; 166; 180; 181; 185; 204).

As a very simple approximation, and with the purpose of taking into account the variation of the upstream concentration, a mass balance equation can be used to model the water quality of the river for one substance in one point (160; 211) (see Equation 5.7).

$$WQO = \frac{(\sum_{i=1}^{n} C_i \cdot Q_i) + (C_u \cdot Q_u)}{Q_u + Q_i} \tag{5.7}$$

where:
WQO = Water Quality Objective;
C_i = initial concentration (concentration of the different sources *e.g.* WWTP effluent, overflows, *etc.*), g/m^3;
n = the number of sources;
Q_i = flow of WWTP effluent, m^3/s;
C_u = upstream concentration, m^3/s;
Q_u = upstream flow, m^3/s.

Accordingly, RPA percepts are the upstream river water quality and the quality of WWTP effluent discharged into the river, as well as flow rates for both, the river and the WWTP discharge. RPA can take these percepts to update its state by means of the simple model presented hereby and to give, as an output, the expected water quality values after the discharge (for an individual pollutant).

The more often considered pollutants include BODr and BODs (readily and slowly biodegradable fractions of biochemical oxygen demand), total ammonia and dissolved oxygen. Discharges into the river include CSOs from the sewer system and storm tank overflows and the treatment plant effluent, as well as direct discharges from industries when the system is collapsed for some reason.

Administration agent models

Economic instruments are one specific type of environmental policy instruments that potentially offer a way to introduce more flexibility and thereby reduce the costs associated with achieving environmental outcomes (89). In order to exemplify the behaviour of the Administration Agent, among the several price-based instruments, we propose to use specific environmental charges (applied to industrial discharges) aimed to reduce the polluting level of a discharge to the environment.

To the general price of the discharge, we propose to add two types of environmental charges with the rate related to the level of an environmental externality, that is, the water quality at the river and/or the affectation of WWTP process.

The effectiveness of prevention - pollution policy is highly related to individual behaviours and the relation between individual interests and environmental ones (144). However, responsiveness to price will also change over time with factors like technology and/or the possible formation of new cluster-coalitions in between them (among other factors). That is, important feedback loops drive the tax-dynamics behaviour. However, for a first approximation, these issues can be avoided.

Some problems arise when using economic incentives to alter the producer's pollution control strategy, such as when:

- taxes are too low (an important drawback of taxes is the difficult precise choice of the most efficient tax level for achieving some predefined objective (106),
- they are used to raise revenue rather than change behaviour, and
- the problem of private information of producer.

When starting an agent-based simulation approach a simple price-based instrument can be used, modifying some values of the main parameters in order to overcome at least the first problem. Different wastewater tax schemes could be proposed in order to:

- in the short term to let industries to discharge at the most convenient place, both for the receiving media water quality (that is, for the whole system) and for industries themselves (less costly) and,

- in the long term to change the wastewater-industrial-production behaviour of industrial producers (since the cost of discharge could be confronted with the production cost, but obviously this will not be achieved during the first approach).

See Box 5.3 for our particular proposal.

5.2.2 Agent communication language: agent interaction protocols and messages

An Agent Interaction Protocol (AIP) describes a communication pattern as an allowed sequence of messages between agents and the constraints on the content of those messages (141). Patterns are ideas that have been found useful in one practical context and can probably be useful in others. Accordingly, AIP provide us with reusable solutions that can be applied to various kinds of messages sequencing we encounter between agents.

We describe the kinds of relations that can exist among individual communicative actions (including both speech acts and non-speech acts) for our specific domain. Broadly speaking the study of relationships within conversations or groups of utterances is studied by researchers of *speech act theory* (23; 50; 183). Parunak in (147) label the basic types of communicative acts. Accordingly, and generally speaking, an individual speech act is either a *solicit* (when the sender wants the receiver to do an act) or an *assert* (an attempt to achieve mutual belief with the receiver that the sender believes the asserted statement). Depending on the kind of action that the sender is soliciting or the nature of the proposition that is asserting these abovementioned speech acts can be more specified (*i.e. request, question, inform, commit* and *refuse*). These individual speech acts led to different kind of relations when two or more agents establish communication to achieve an objective that can not be achieved alone; that is, every initiating speech act needs or is linked with an appropriate resolving one (*e.g.* a question is resolved by an appropriate *inform*, or a *request* is resolved by either a *refuse* or a *commit*), leading to a sequence of communicative acts.

The Foundation for Intelligent Physical Agents (FIPA) develop specifications for agent communication providing standard communicative acts and interaction protocols. The objectives of standardizing and defining communicative acts are the following (75):

- to help ensure interoperability by providing a standard set of composite and macro communicative acts, derived from the primitive communicative acts (*e.g.* request, question, inform, commit, refuse);

- to facilitate their reusability;
- to provide a well-defined process for maintaining a set of communicative acts and act labels.

The message is structured at least with the following parameters:

- *Sender*: initiating participant in communication.
- *Receiver*: addressee participant in communication
- *Performative*: type of communicative acts
- *Protocol*: the interaction protocol that the sending agent is employing when sending the message
- *Content*: denotes the object of the action and its meaning is intended to be interpreted by the receiver of the message. Depending on the type of performative the content is a simple proposition (*e.g.* denoting an action to be done) or a *tuple* (*e.g.* the first part consisting of an action expression denoting the action to be done and the second a proposition giving some conditions)

The messages sent and received by the agents are the implementation of the interaction protocols. These interaction protocols have been instantiated for the agent-based model of the UWS, and graphically depicted in Figures A.1–A.18 in Appendix A. The specification of messages together with the performatives used are shown in Tables A.19–A.20. Finally, a sequence diagram is depicted to emphasize the chronological sequence of communication (Figure A.21).

5.3 Organizational model

An acquaintance model may be easily derived from the roles, protocols and agent models. Usually is depicted as a graph with nodes corresponding to agent types and arcs to communication pathways. It gives an overview of the connections among agents and the existing communication pathways.

Figure 5.7 shows the acquaintance model for the urban wastewater management scenario. It is important to say that the acquaintance model specify which agent interacts with which but it does not show explicitly the situation in which an agent can interact with another agent (*e.g.* just responding to a request) without having necessarily any knowledge (information) about it.

5.4 Conclusions

In this chapter the application of an agent-based approach has been especially appropriate for the study of the UWS focusing on:

- Behaviour: we have moved from components to the description of *agents* with their own *roles*. We have seen that the behaviour of agents can be incorporated by using either simple rules or more complex models whose computation would require external software packages.
- Communication: agents need to interact with other agents to execute their roles, since the intelligence of the overall agent-model is distributed among many agents representing specific entities of the real world. Such interactions can be naturally depicted and explored using agent-based technologies.
- Qualitative information: agent-based models permit, in some occasions, to include incomprehensible qualitative behaviour better than conventional models (*e.g.* differential equations).
- Dynamic system representation: agent-based models allow the model structure to be variable. Agents can be added and others can be deleted. However, and due to some limitations of the approach used (*e.g.* the fixation of specific roles to agents), the interactions among agents are decided according to the system goal in the phase of design. As a result, an agent cannot change its roles at run-time.

Further discussion on the suitability of the agent-based conceptualization is given in Chapter 8.

Box 5.3. **Econometric Model.** The price of the discharge at each time for the industry is a function of the following parameters:

- The *volume* of the discharge (quantity of wastewater produced).
- The *type of industry* (taxes *w.r.t* industry potential pollution).
- *WWTP state*: the price of the discharge into the sewer system and thus to the WWTP increases with the occupied volume of WWTP (see Figure 5.6-a) as well as the cost to treat the incoming discharge according to their concentration of pollutants.
- *Industrial Tank state*: the cost to store wastewater at industrial tanks will increase as well with the occupied volume of the tank, but at a potential rate (see Figure 5.6-b).

The model is conceptually depicted in Figure 5.6 and shows how the price of discharge changes depending on the occupied volume at both, the WWTP and Industrial Tank. It is important to note that the curves will depend on the specific discharge, and calculated at each time step for each proposed discharged. Thus the slope of the curves will change according to each specific discharge as follows (see Equation 5.8):

$$P(i,t) = f(volume, type, wwtp); P(i,t) = UP(i) \times [1 + P(IndTank; WWTP)] \quad (5.8)$$

where:
P(i,t) is the discharge cost for industry i at time t;
UP(i) is the unitary price of the discharge and is described in Equation 5.9:

$$UP(i) = V \times [GT + ST(i)] \quad (5.9)$$

where:
GT is the General Tax and
ST is the Specific Tax (dependant on the type of industry).
P(IndTank) is the cost to discharge into industrial storage tanks. It depends, as shown in Figure 5.6-b on the occupied volume of the tank. The occupied volume of the tank changes at each time according to the inflows and the outflow (Q_{out}) of the tank. The inputs to the tanks are the proposed industrial discharges (Q_{ind}). Thus, the occupied volume of the tank (*VocTank*, m^3) at the time t can be described as follows (see Equation 5.10):

$$V_{ocTank} = V_0 + (\sum Q_{ind} - Q_{out}) \times t \quad (5.10)$$

Accordingly, the price to discharge into the storage tanks will be:

$$P(IndTank) = UP(i) \times (1 + \frac{V_{ocTank}}{V_{totTank}})^x \quad (5.11)$$

where x is a potential factor, giving the idea that the price increases quite a lot when the tank is fuller.
P(WWTP) is the cost to discharge into the WWTP (through the sewer system) and, in the same way as the tanks, is described in Equation 5.12:

$$P(WWTP) = UP(i) \times (1 + \frac{V_{ocWWTP}}{V_{totWWTP}}) \quad (5.12)$$

(cont'd of Box 5.3.)

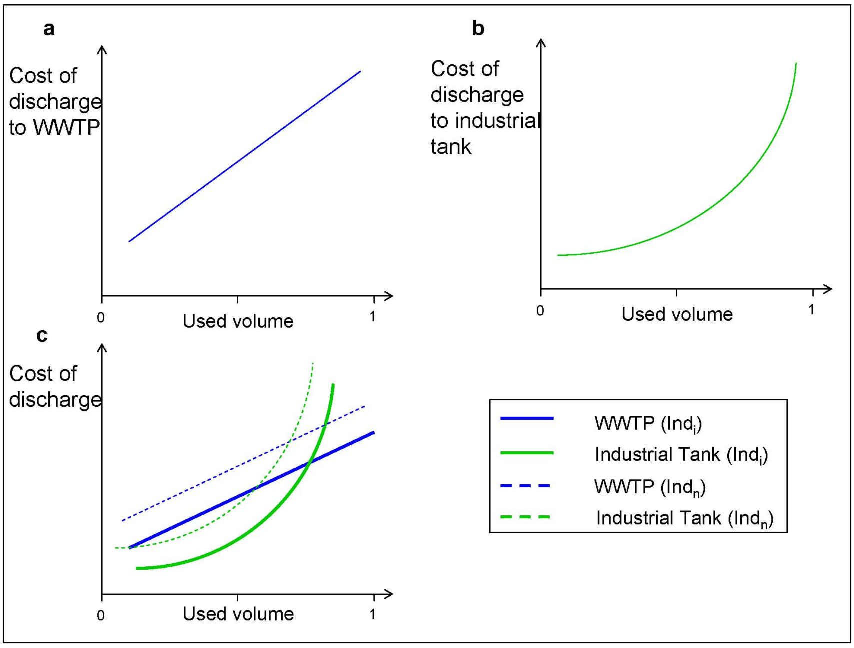


Figure 5.6: Cost model

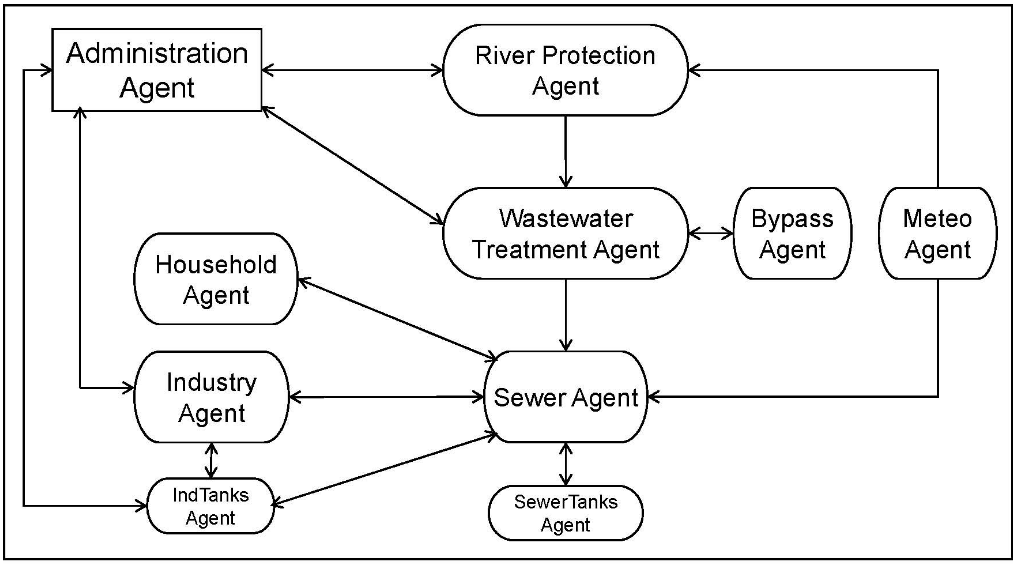


Figure 5.7: Acquaintance model

Chapter 6

Agent's reasoning approach: knowledge specification

In this chapter a framework able to capture the knowledge used by agents for reasoning about problems at the river basin scale is proposed. This framework is specially addressed to model in a possibilistic declarative way that knowledge that might be helpful in situations of disagreement, conflict and uncertainty. For this purpose it is used Answer Set Programming (ASP) *a* declarative language *together with possibilistic theory. By giving an example, concretely for diagnosing the safety of industrial wastewater discharges in the system, we illustrate how to represent relevant abstractions to model complex processes and how, by using them, it is possible to automate the diagnosis process. Then, we introduce an argumentation-based approach in order to decide which of the several diagnoses (i.e. answer sets) is the winning one for a given situation. Using these frameworks, it is possible to deal with uncertain and inconsistent knowledge bases, and hence to support the decision-making task in complex domains such as the wastewater management domain.*

6.1 Introduction

As introduced in §2.1.2, with the adoption of the WFD (42), all European countries have committed themselves to a river-basin water management approach. The WFD proposes to assess the water quality of water bodies in a river basin by using more holistic environmental standards *i.e.* not only chemical or physical. It proposes to define

River Basin Plans which must define objectives for each water body considering social, environmental and economic factors (these are key points to be tackled by decision-making processes at river basin scale) (68; 107).

Although the decisions are inherently a political issue, there is a growing awareness that plans need scientific groundwork and the support of all involved *stakeholders* prior to their implementation (66). In order to support the planning and implementation of measures as well as the communication among the different *agents* at the river basin, it is essential to carry out an integrated and informed approach, on the basis of system diagnosis, that enable to compare river basin strategies based on the effects on multiple objectives. An integrated river basin management approach requires knowledge and expertise to describe the effects of different combination of measures and scenarios.

The conditions related to the management of water and wastewater systems are highly variable and sometimes even unpredictable. Climatic, demographic, industrial and management or planning factors are the main sources of this variability that entails to consider more flexible ways to manage them. Some of the typical traits of environmental systems, such are river basins, are described by Rizzoli and Young in (167) and summarized in §2.3. The dynamics of environmental systems, their spatial coverage, the complexity and system cybernetics, together with the type of information and knowledge usually based on approximate or imprecise quantitative/qualitative data, makes the decision process in these contexts a complex task.

Thus, in the area of environmental management, it is important to find new ways to model and integrate the cause-effect relationships of actions and to represent the knowledge in an effective way to enable comprehensive reasoning. As pointed out in Chapter 1 the use of knowledge-driven approaches in the area of environmental modelling is well supported in a recent review by Villa *et al.* (206). However, knowledge management and knowledge based decision processes are still a challenge in this domain (59; 104; 127; 167). According to Mikulecký in (127) knowledge-based approaches can help to resolve many of the problems related to more efficient and effective operations in a number of important or even dangerous situations which appear in river basins.

In this chapter, we propose a way to give an answer to two significant questions related to knowledge-based modelling in the environmental domain and in particular in integrated river basin management *i.e. 1. How to represent and integrate cause-effect relationships?* and, *2. How to represent the relevant knowledge to allow effective reasoning in the context of river basins?*. Resolving the first question will lead to a better understanding of the complex connections between the several river basin system components (see Chapter 2). Once these relationships are identified, it is essential to apply the new valued knowledge to support the resolution of real problems. That is, and in response to the second question, to find ways to effectively represent and specify these important connections using computational languages. This leads to make this complex knowledge explicit and hence, usable.

The rest of the chapter is organized as follows: in §6.2, we present a simplification of the context under study. We settled and contextualized water pollution as an important problem to be dealt with in urbanized river basins. In §6.3 the proposed framework to structure and specify the related domain knowledge is presented. Concretely, in §6.3.1 and in response to the first question, various automata of finite states for considering impacts given a specific driver, such as industrial wastewater discharges, are described based on the classical automata theory (92).

In §6.3.2, and in response to the second question, it is presented the layered methodology to structure the river basin domain knowledge in order to facilitate the formalization and implementation of it for reasoning purposes. The specification of this knowledge as well as some results of a concrete case example are described in section §6.4 according to the issues introduced in §4.4.2. Finally, in section §6.5 a brief discussion about this reasoning approach is portrayed.

6.2 River basin management: integrating emergent industrial wastewater discharges

Integrated Urban Wastewater Systems (IUWS) are systems composed of several components. The most important ones are industries, households, sewer system, WWTP and the river (37; 81; 175; 203). Several aspects govern this system:

- wastewater discharge-related aspects, that is the identification of wastewater sources, treatments and impacts;
- community-related aspects, that is, the population and the socioeconomic settings, and
- government/ administration-related aspects, that is institutional arrangements, regulations, policies, strategies and actions, in which government/administrative parties play an important role.

In this context, determining the threat of wastewater sources to assess the safety of actions is a key issue for the sustainable use and conservation of the resource. In urban or industrial-dominated basins water pollution is an important problem of concern. Any single action or intervention has implications for the system as a whole since all the components are interconnected.

According to Mikulecký *et al.* (127) and Lautenbach *et al.* (107) there are some important issues that need to be studied when dealing with a knowledge-based approach of urban basin management, as well as to limit the problem under study. These issues are grouped into *management actions*, *management objectives* and *constraints*. In relation to the IUWS the following issues will be considered:

1. *Management actions*: these are the introduced management options under study at the UWS scale. Focusing on our scenario, these will be those measures at catchment scale aimed at reducing pollution from industrialized urban areas. We assume that industries can *get rid off* of their wastewater by connecting to the public sanitation system, so the municipal wastewater treatment plant will treat it. Obviously, this action can be performed under some conditions and constraints. This action is supported by sanitation plans in order to maximize the use of municipal sanitation infrastructures (1; 2), and it is constrained by some regulations (128). They can also discharge directly to the WWTP using a tanker, given some special circumstances and with special permission from the environmental administration responsible for the receiving treatment plant. Or finally, they can discharge to the river, only if it is considered better for the system, because of sufficient industrial pre-treatment, or because of, given some situation, the will to prevent worst damage to the sanitation system (Figure 5.1 depicts all these possibilities). We will consider the most common situation that is, the connection of industries to the municipal the municipal WWTP through the sewer system.

   Then, several management options can be applied[8]:

   - Industrial pre-treatment: the application of a pre-treatment at industry site leads to the reduction and/or elimination of specific substances.
   - Industrial tanks: the construction of industrial tanks to temporarily store the discharge permits to retain some industrial discharges that can then be released to the system or can be sent to a specific wastes' manager.

[8]Note that these actions correspond to some agents' functions/services described in Chapter 5.

  - Combined sewer tanks: the construction and use of sewer tanks permit to retain and laminate rainfall and storm events in order to prevent hydraulic shocks and sewer system overflows. In unitary systems, these tanks can store the rainfall together with the wastewater coming from different sources, so if an overflow occurs this will be combined (white and black waters).
  - Improve treatment plant technology: the improvement of WWTP may lead to an increase of substance elimination and WWTP efficiency. These also includes the possible pre-treatment and operational specific measures that can be performed.
  - Improve sewer system: in order to improve drainage capacity, avoid infiltrations and leaks, *etc.*
  - Bypass: on the one hand, this action consists on the construction and/or use of bypasses between two WWTPs permitting to maximize the use of infrastructures when one treatment plant can not handle the influent. On the other, is to bypass wastewater between the primary treatment and the river in order to avoid organic or hydraulic shocks to the WWTP; however it can damage the final receiving media.

2. *Management objectives*: these must be shown in relation to legal thresholds or other meaningful factors. These can be abstracted from current institutions *i.e.* European directives, national laws and local agreements (see §2.1.1). Examples of those high-level objectives are *reduce emissions*, *prevent overflows*, *prevent sanitation system failures*, *etc.* WFD gives objectives in terms of the achievement of specific *status* of water bodies *w.r.t* . several factors (*e.g.* sensitivity, water uses, *etc.*). The proposed measures are aimed to achieve the main goal of the integrated river basin management approach, that is to achieve a good ecological status of water bodies *e.g.* the river.

3. *Constraints*: *external constraints* are components similar to management actions but they do not offer as many modification options as management actions. These are, in our knowledge-based model (see §6.3.2), the global complexes, *e.g.* weather seasonal variations, demographic growth, development of industrial areas, *etc.* Similarly, there exists *internal constraints*, most of them deduced from regulations. Specifying a constraint as *hard*, that is a constraint that cannot be violated, presumes an infinite cost of failing to enforce it.

The well description of these issues is useful to depict the cause-effect relations of a *management action* to the system possible *states* (see Figure 6.2 in §6.3.1 in which the arrows of the automata represent the possible management actions of the system).

After introducing the main issues of the context under study, we proceed to present the methodological approach to structure the knowledge related with them.

6.3 Methodological approach

Figure 6.1 depicts the several steps of the knowledge-based proposal. Firstly, and in relation to the challenge of *how to represent the cause-effect relationship* of the aforesaid *management actions*, we propose to abstract these relations in a diagram that can then be instantiated according to a specific situation (see §6.3.1). Secondly, the knowledge used to define these situations is inferred from the well structured domain information (see §6.3.2). Finally, the codification of the domain knowledge as well as of their interrelations is done to automate the process of diagnosis (see §6.4). The solutions, (in the form of *answer sets*), enclose the possible system state diagnosis given a specific situation. That is, the set of possible relevant conclusions that should then be taken into account by wastewater managers.

On the basis that for each diagnosis there is at least a protocol of actions, it appears the possibility to consider to built plans of actions from the diagnose's layer of the knowledge-based framework . This possibility is as well depicted in Figure 6.1: the knowledge obtained from the diagnosis process can then be used to support decisions in the river basin large-scale. However, to support the deliberation process to evaluate the possible answers, some other tools are needed. As introduced in §4.4, argumentation processes are reported to be useful to evaluate the possible solutions, principally if there are lots of stakeholders (namely MAS) involved (124; 196).

6.3.1 Automata-based model for depicting cause-effect relationships

In Figure 6.2, two diagrams that express the transitions between different states or situations are presented. The automata presented in this paper have been described using the following relevant aspects in relation to the issues introduced in §6.2, and with the purpose to simplify the possible system situations:

- Industrial discharge wastewater-related aspects (D), according to the amount and type of pollution.

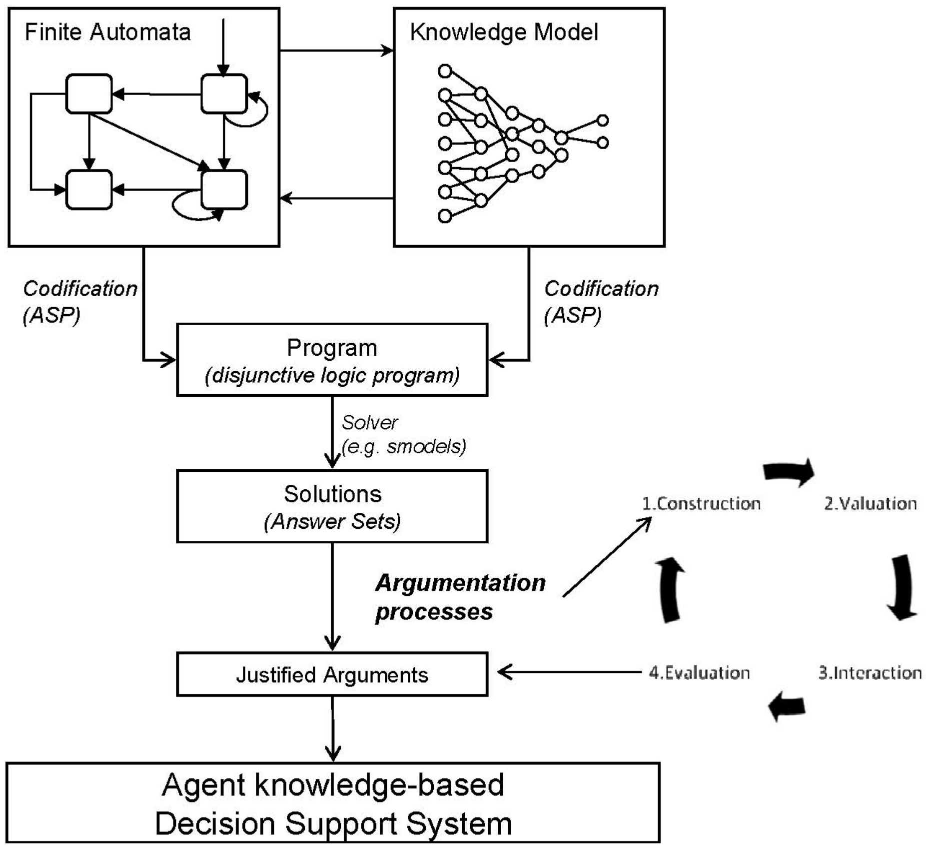


Figure 6.1: Knowledge-based methodology for decision-support in river basins

- WWTP operational situation (*WT*) denoting the sate of the treatment plant. It is noteworthy to mention the work of (84) *w.r.t* this specific aspect (*i.e.* cause-effect relationships among WWTP operational states), that it is pioneer to this kind of modelling in the wastewater management field at the treatment plant level.
- WWTP effluent characteristics (*WWTP_eff*) denoting a type of treated effluent. The classification of specific effluent discharges threat allow the municipality and the operator of the WWTP to define different policies to prevent risks (60).
- River state (*River*) that denote *normal* state or some *problem* in the river.

Accordingly, each node represents a possible situation in which the system can be found and the arrows represent possible river basin management actions. This global automata can be instantiated according to a particular situation. For example, Box

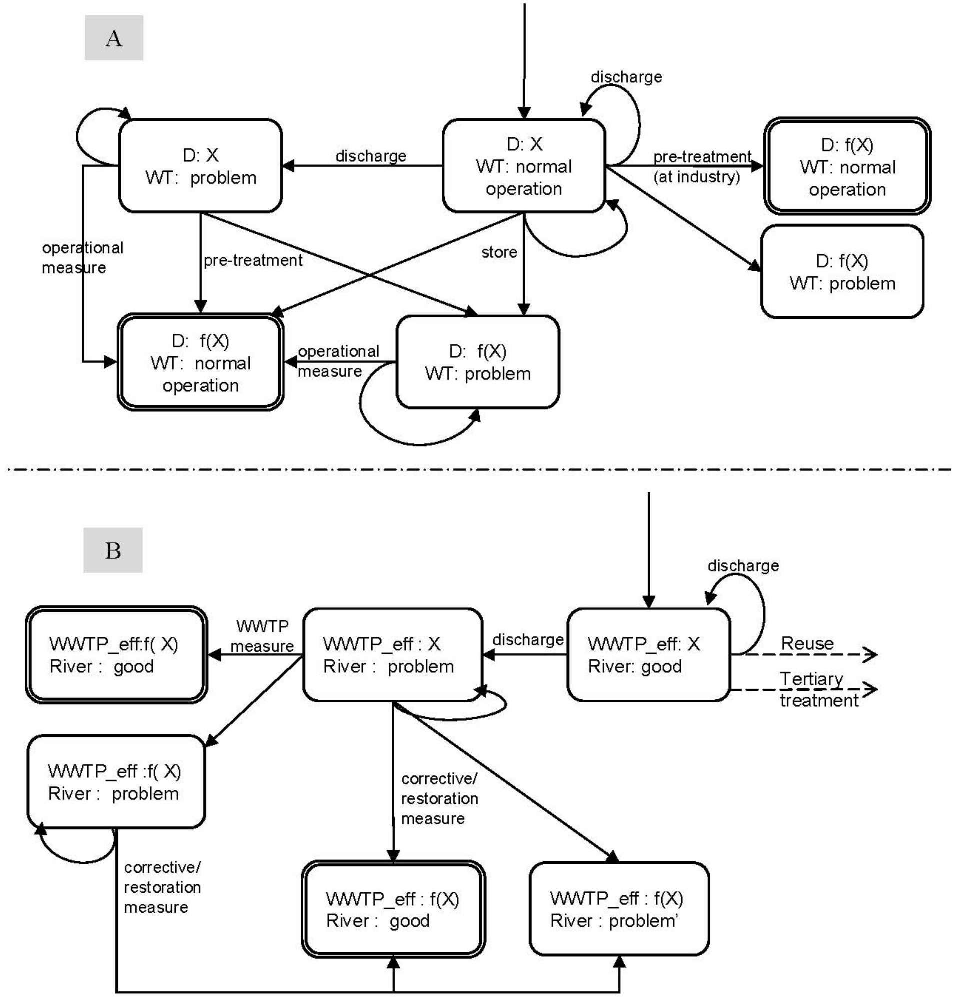


Figure 6.2: An automata of finite states for considering **A**: problems at *activated sludge* municipal WWTPs given an industrial discharge and **B**: problems at rivers given a WWTP effluent

6.1 contains a possible industrial wastewater discharge situation, which is instantiated in Figure 6.3 and codified in Box 6.2. Note that we have added the line of time (T) in order to show the temporal dynamics between states. Note that the function *f(X)* expresses a transformation process, that is, indicates a change in the value of D. So, it supposes the existence of functions and/or models to express the transformation of pollutants, substances, *etc.* (see §5.2.1).

> Box 6.1. Among the various problematic and complex scenarios ongoing in the context of *river basin systems*, we are going to consider ***industrial wastewater discharges*** as a particular domain scenario in industrialized river basin systems. In order to constraint this domain scenario the following situation is presented:
>
> > Suppose that an industry dedicated to the production of yoghurts faces a problem in the production system, and the acid lactic bacteria producing medium needs to be replaced. This implies a complete breakdown in the production, the cleaning and disinfection of all tanks with the consequent washout of the acid lactic producing bacteria, together with the current production of yoghurt. While common emissions from the diary industry are biodegradable, this situation will imply a considerable amount of wastewater with high content of organic matter, fats and greases from the milk, as well as a low pH due to the acid lactic bacteria medium.
>
> Given this scenario, water managers want to know which are *the possible impacts* that might hit the river basin system if the discharge is made.

At this stage the attention is away from any particular kind of computer or particular programming language. However, the representation in terms of finite states suits well with the proposed specification (see §4.4.2), since each arrow is interpreted as a possible cause-effect propositional rule.

In our particular scenario (see Figures 6.2 and 6.3) we are assuming as *normal operation* the initial state of the WWTP, and as *good* the situation of the river (time *T0*). However, the characteristics of the discharge are *very low pH* and *very high* BOD_5 load, which can cause several problems at the receiving treatment plant resulting in a problematic WWTP effluent, and consequently reducing the river system quality. From the initial state, the system actions can be either to make the *discharge* to the sewer to be treated by the municipal WWTP, or to perform some actions at the industry, that is, to temporarily *store* it or to perform a *pre-treatment*. According to Figure 6.2-A, a WWTP can be found in different situations after the action is done (time *T1*): to have or not a problem. Therefore, if a problem is present, the system may require other actions to prevent (pre-treatment measures at WWTP) or correct (operational

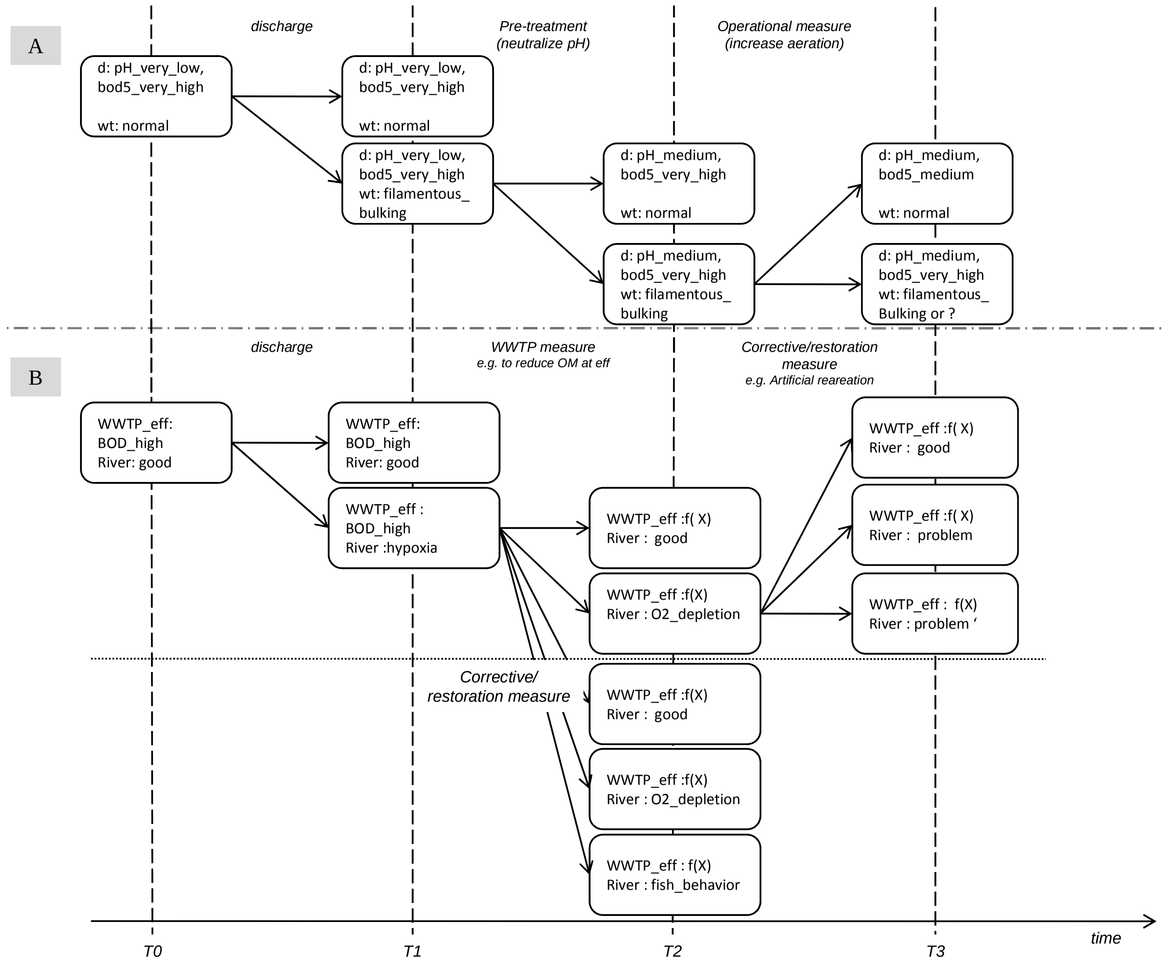


Figure 6.3: An instantiation of the automata presented in Figure 6.2 to diagnose the safety of the industrial discharge at the municipal WWTP (**A**) and after to the river (**B**)

measures at WWTP and corrective/restoration measures at the river) the problem. Obviously, the desired actions will be those letting towards *normal operation* for the WWTP and *good* situation for the river as final states.

The well description of the above river basin states or situations needs relevant domain knowledge. The organization and representation of this knowledge is as important as the knowledge itself, since it reduces the difficult task of accessing, sharing and using it. Therefore, in §6.3.2 we propose to structure the river basin complex knowledge in a layered framework.

6.3.2 A framework to model the domain knowledge

In the river basin domain, some approaches exists specifically to improve and increase knowledge on WWTP's operational problems related to influent characteristics *e.g.* (20; 52; 53; 91; 96). This knowledge is often structured and organized by means of decision trees based on cause-effect relations for a concrete problem (57; 157; 168; 178; 179). Although decision trees are a very popular way to represent knowledge, this type of organization tends to perform well if a few highly relevant attributes exist, but less so if many complex interactions are present, such in the abovementioned domain. The need for more flexible knowledge inference relies on structuring the information in different levels. Otherwise the rule system reflecting the decision trees is too static for adaptation to each situation and not always permits to represent complex interactions (44).

In order to systematize and constrict the agent's reasoning, the knowledge in the river basin domain can be described by means of multiple layers each one containing some specific type of knowledge. The reasoning process can then be expressed by the various relations in between these layers, as a process of taking the information from these different levels. Accordingly, the higher levels entail or provide a context for the interpretation of the lower levels (*e.g.* observations can be interpreted as a consequence of potential WWTP problems). The model here presented is based on the approach of Evans and Gadd (72).

The following levels are considered:

1. *Empirium*: is the first level, which corresponds to sensory data. It carries no environmental interpretations, such as solid separation problems or high temperature (*e.g.* on-line sensors, analytical determinations, list of polluting substances related to an industrial activity, *etc.*).

2. *Observations*: is the second level, which corresponds to perceptual categories that

require more expert knowledge. For example, odours, colours, visual state of some elements, levels or degrees of the abovementioned empiriums, *etc.*

3. *Findings*: is the third level and corresponds to groups of observations that are interpreted in terms of their environmental relevance. For example low Dissolved Oxygen (DO) concentration and high Biochemical Oxygen Demand (BOD_5) is interpreted in the context of eutrophication in rivers. Or a cluster of observations that suggests some characteristic of the polluting substance (*i.e.* toxicity, bio-eliminability, persistency, bio-accumulation, solubility, *etc.*).

4. *Facets*: is the fourth level and represents sub-diagnostic categories that suggest potential diagnoses; facets capture patterns of findings, that is, a distinct feature in a problem (*e.g.* one of numerous aspects of some potential diagnoses). For example, a cluster of findings *i.e.* nutrients deficiency, low pH, high Readily Biochemical Oxygen Demand (RBOD), serves to explore a particular subset of WWTP problems while discarding others.

5. *Diagnoses*: is the fifth level which corresponds to categories of problems with more or less known explanatory and solution plans.

6. *Global Complexes*: is the sixth and last level which holds the circumstances that affect a particular river basin, such as particular rainfall regimes that may influence a diagnosis or management pathway.

The classification in these levels permit to narrow the diagnostic of problems in the system by integrating:

- the space of empirical manifestations (the level of *empirium* and *observations*),
- the space of possible problems within the system (that is the level of *facets* and *diagnoses*),
- the constraints to explore, such as the contextual or causality relationships between specific problems and empirical manifestations (the level of *findings*),
- and the specific conditions for each river basin or a particular component in the system (level of *global complexes*).

It is important to note the consideration that the lowest knowledge level entails no uncertainty *i.e.* the level of *empirium* data (*e.g.* the consideration of no uncertainty

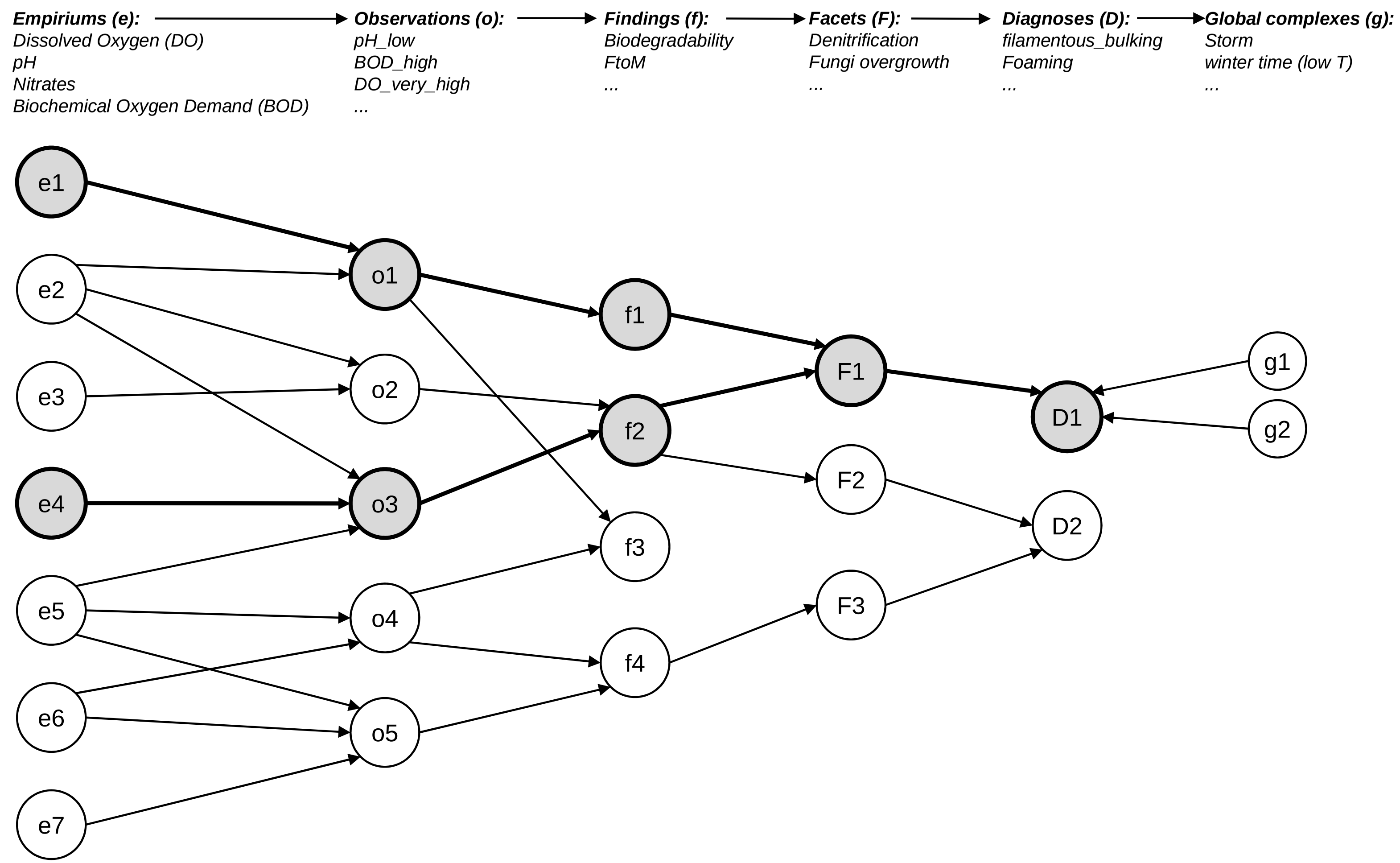


Figure 6.4: Knowledge-based framework for river basin problem solving. Bold arrows show a possible diagnosis reasoning path in which D1: `filamentous_bulking` can be inferred from the multiple layers of concept types (in grey)

on the data coming from sensors, lab analysis or tests, *etc.*), whereas the uncertainty increases going into the upper levels.

It is proposed to use this model to structure the knowledge base of an intelligent agent applied to river basin management, concretely for the decision-making and problem-solving tasks. Classifying the domain knowledge like this permits to focus only on the necessary and specific knowledge for each decision process, and even to omit some strata in the knowledge structure depending on the assessed type of problem. For example, if the initial available data refers to a finding of a specific industrial discharge (*e.g.* toxicity) so, the level corresponding to empirium is not present (*e.g.* it is not available an exact description of the discharge content), it is still possible to assess decisions by means of interpreting the potential problems using the knowledge level of findings.

In §6.4 the suitability of using a logic program to capture these problematic situations will be discussed. The previously described automata, whose states are described by means of the proposed knowledge-based framework, will be implemented using a declarative language. In fact, each arrow of the automata can be expressed by an effect proposition. This language is based on a possibilistic approach that enables to capture knowledge bases with uncertain, inconsistent and incomplete information (135; 137).

6.3.3 Building possibilistic arguments

As it was pointed out in §4.4.1, the first step in the inference process in argumentation theory is the construction of arguments from a knowledge base. Hence, in this section, it is defined how to build possibilistic[9] arguments from a possibilistic program.

A possibilistic argument can be constructed by considering any possibilistic logic programming semantics[10] *i.e.* the possibilistic stable semantics, the possibilistic answer set semantics, the possibilistic pstable semantics (134; 136; 143). Classically, in logics, one only believes those statements that can be (mathematically) proved. In this fashion,

[9] In contraposition to probabilistic, possibilistic logic is a weighted logic introduced and developed in the mid 1980s, in the area of artificial intelligence, with the aim to develop a simple and rigorous approach to automated reasoning from uncertain or prioritized incomplete information. Possibilistic logic is specially adapted to automated reasoning when the available information is vague or imprecise. In fact is an extension of classical logic where the notion of total/partial order is implanted in the logic (135). In contrast to deterministic systems, possibilistic systems leave some uncertainty in the specification of future states and behaviour, even if all relevant conditions are known.

[10] In theoretical computer science, formal semantics is the field concerned with the rigorous mathematical study of the meaning of programming languages and models of computation. The formal semantics of a language is given by a mathematical model that describes the possible computations described by the language (169).

possible worlds can be built. Consequently, given a non-monotonic framework (see §4.4.1) two points of view to handle conflicts arise:

1. Conflicts between defeasible conclusions and "hard facts", some of which possibly newly learned; and

2. Conflicts between one potential defeasible conclusion and another (many formalisms, for instance, provide some form of defeasible inference rules, and such rules might have conflicting conclusions).

When a conflict of either kind arises, steps have to be taken to preserve or restore consistency. All non-monotonic logics handle conflicts of the first kind in the same way: indeed, it is the very essence of defeasible reasoning that conclusions can be retracted when new facts are learned. But conflicts of the second kind can be handled in two different ways: one can draw inferences either in a *cautious* or *bold* fashion (also known as *skeptical* or, respectively, *credulous*). These two options correspond to significantly different ways to interpret a given body of defeasible knowledge, and yield different results as to what defeasible conclusions are warranted on the basis of such a knowledge base.

Since one can consider the skeptical and credulous versions of possibilistic semantics, two kinds of possibilistic arguments can be defined: *brave possibilistic arguments* and *cautious possibilistic arguments*. The formal construction of these types of arguments is formally described in Definition 6.1 by Nieves in (135).

Definition 6.1 (Possibilistic Arguments) *Let* $P = \langle(\mathcal{Q}, \leq), N\rangle$ *be a possibilistic logic program. A possibilistic argument* Arg *w.r.t* P *is a tuple of the form* $Arg = \langle Claim, Support, \alpha\rangle$ *such that the following conditions hold:*

1. $Support \subseteq P$.

2. $Support$ *is minimal w.r.t set inclusion.*

3. $\exists\ M \in S(Support)$ *such that* $(Claim, \alpha) \in M$ *(in this case the possibilistic arguments* Arg *is called* brave*. When the existent quantified* $\exists$ *is changed by the for all quantified* $\forall$*, the possibilistic arguments* Arg *is called* cautious*).*

S *is any possibilistic logic programming semantics.*

The first point of Definition 6.1 indicates that, in order to build arguments, the support is part of the available knowledge base, and the second indicates that it is required the minimum possible information to support the conclusion. The last point, intuitively, comes to the difference between the abovementioned basic attitudes, *i.e.* *credulous* or *skeptical*. In the presence of potentially conflicting defeasible inferences (and in the absence of further considerations), the *credulous* reasoner always commits to as many defeasible conclusions as possible, subject to a consistency requirement, whereas the *skeptical* reasoner denies agreement from those potentially conflicted defeasible conclusions (*i.e.* is more cautious).

In §6.4 of this chapter we show how from the program of our case study we built the corresponding possibilistic arguments. Observe that Definition 6.1 considers two steps of the inference in argumentation presented in §4.4.1: *argumentation construction* and *argumentation valuation.*

Remark 6.1 *Before to follow on, we want to point out to the reader that to build an argument* `Arg` *with conclusion* `a` *from a program* `P`*, it does not mean that* `a` *is a correct conclusion of the whole program* `P`*. For instance, from Box 6.4, the existence of the possibilistic argument* `arg3` *which suggests that the WWTP can have the problem of filamentous bulking, it does not mean that* `arg3`*'s conclusion is a correct conclusion of the whole program* `P` *of Box 6.2. The acceptance of the* `arg3`*'s conclusion will depend on the interaction of all the possibilistic arguments that one can build from* `P` *and the pattern of selection of arguments (argumentation semantics) that one uses for fixing the status of the arguments.*

6.3.4 Interaction between possibilistic arguments

As it was pointed out in §4.4.1, the second step in the inference process in argumentation theory, after having built the arguments, is to find the relation between them. This means to introduce the possibility of debate, that is, to find the defeat relations *e.g.* relations of attack or support between the arguments.

In other words, we will define the cases when two possibilistic arguments will be in a conflict and then to define which arguments will be considered accepted according to a pattern of selection (argumentation semantics).

Usually the relation of *attack* between arguments is defined in terms of complementary atoms *i.e.* a and $\neg a$. The formal relation of *attack* between possibilistic arguments is written in Definition 6.2 (135).

Definition 6.2 (Attack relations) *Let* Arg_1 *and* Arg_2 *be two possibilistic arguments such that* $Arg_1 = \langle Claim_1, Support_1, \alpha_1\rangle$ *and* $Arg_2 = \langle Claim_2, Support_2, \alpha_2\rangle$*. We say that* Arg_1 *attacks* Arg_2 *if one of the following conditions hold:*

i) $Claim_1 = l$, $Claim_2 = \tilde{l}$ *and* $\alpha_1 \geq \alpha_2$.

ii) $\exists(q : l \leftarrow \mathcal{B}^+,\ not\ \mathcal{B}^-) \in Support_2$ *such that* $\widetilde{Claim_1} \in \mathcal{B}^+$ *and* $\alpha_1 \geq \alpha_2$.

iii) $\exists(q : l \leftarrow \mathcal{B}^+,\ not\ \mathcal{B}^-) \in Support_2$ *and* $Claim_1 \in \mathcal{B}^-$.

Intuitively, the meaning of Definition 6.2 is that the attack relations occur when the first argument attacks the premises of the second one. Accordingly, there are two possible ways of attacking premises:

- The atom is complementary (expressed by condition *i.*): the claims of the (two) arguments are complementary and the degree of confidence of both arguments are equal or the first is higher than the second.

- The atom is negated using negation as failure (expressed by conditions *ii.* and *iii.*): condition *ii.* expresses that the head of the first argument is negated by the body of the second one and its degree of confidence is the same or higher; condition *iii.* expresses that the conclusion of the first argument is negated in the premise of the second one (which attacks).

The attack relations between the arguments of our specific example are shown in Box 6.5 of §6.4. Once there have been identified the relationship between possibilistic arguments, we require to evaluate the relationship between these arguments. The process is briefly described in §6.3.5.

6.3.5 Argumentation status evaluation

The last steps in the inference process in argumentation theory are to find out the justified arguments and the acceptable set of arguments (*i.e.* conclusions) depending on a specific semantics applied.

The evaluation of the interaction between arguments is an important step in the inference of argumentation (see §4.4.1). In argumentation literature, there are several approaches in order to select coherent points of view from a set of arguments in conflict (48; 158). In our case, we will follow Dung's argumentation style (71). This approach is based on the structure called *argumentation framework*. We will generalize the concept of argumentation framework into the concept of *possibilistic argumentation framework*, such as described in the following Definition 6.3 by Nieves in (135).

Definition 6.3 (Possibilistic Argumentation Framework) *Given a possibilistic logic program, a possibilistic argumentation framework AF w.r.t P is the tuple* $AF_P^S =$

$\langle \mathcal{ARG}_P^S$, *Attacks*$\rangle$, *where Attacks contains the relations of attack between the arguments of* $\mathcal{ARG}_P$.

We are essentially instantiating Dung's argumentation approach into possibilistic arguments. According to Definition 6.3, a Possibilistic Argumentation Framework (AF_P) is the tuple formed by the possibilistic arguments and their attack relations (*attacks* contains the relations of attack between the arguments of an argumentation base).

Once we have instantiated a possibilistic program P into a possibilistic argumentation framework AF_P (see the AF_P in Box 6.6 for our specific case), we can apply an argumentation semantics to AF_P in order to infer information from P.

In argumentation literature, we find that the most accepted argumentation semantics are the *grounded, stable* and *preferred semantics* suggested by Dung in (71) (see §4.4.1 for a brief explanation of the meaning of these semantics or patterns of selection). The objective of these semantics is to select subsets of arguments from a set of arguments such that these subsets of arguments represent coherent points of view from a conflict. By coherent point of view, we mean that a set of arguments inferred by an argumentation semantics must be *consistent* and moreover it must be *a defendable position* in a conflict of opinions.

In order to study a relationship between the argumentation inference and the inference of some possibilistic logic programming semantics, Nieves in (135) define the projection ϕ which is a relation from $\mathcal{ARG}_P$ into $2^{\mathcal{PS}}$ such that given a set of possibilistic arguments $\mathcal{ARG}$, $\phi(\mathcal{ARG}) = \{(a, \alpha) | \langle a, Support, \alpha\rangle \in \mathcal{ARG}\}$. This generalization is exemplified for the presented case study in Box 6.7.

Some formal properties emerge from the definitions hereby presented *w.r.t* consistency and conflict-freeness of information. The interested reader can refer to (135).

6.4 River basin decision-support agent for the industrial wastewater discharge case

The aim of this section is to qualitatively described the case presented as an example application of the argumentation knowledge-based agent proposed framework. In Box 6.2 a piece of the program that codifies the example in Box 6.1 is shown. A brief description of this program is given together with the possible answer sets.

Let us consider the case presented in Box 6.1 which informs that the wastewater discharge has a very low pH and a very high BOD_5. The knowledge base of this example is encoded in Box 6.2 and it is structured by means of the layered methodology presented in §6.3.2. Observe how, in the case of diagnosing problems in our system, the environmental knowledge involved can be described as a knowledge base with multiple layers of concept types (*i.e.* observations, findings, *etc.*), and various relations in between. These relations describe patterns that can be used to explained diagnostic reasoning as a process of abstracting case information from different levels. For example, and in this case, the specific observations suggests to be the cause of several problems at the WWTP and hence to the river.

These inferences are captured using the disjunctive clauses presented. The intended meaning of clause (1) is that if the industrial discharge contains a very high load of organic matter (measured in terms of BOD_5), the WWTP can undergo or not a problem (*e.g.* clause (1) represents specifically *filamentous_bulking*, since there is not evidence of having the other possible problems given the initial observations). Clause (2) is another type of clause in which the head is strongly negated. The intended meaning of this clause is that it can be concluded that the WWTP has no problems if there can not be found evidence of any problem at the WWTP. Clause (3) connects some of the relevant factors of automata depicted in Figure 6.2-A and Figure 6.2-B. The intended meaning is that if the WWTP undergo one of the problems considered in the knowledge base, the WWTP effluent (*wwtp_eff*) might result *organic_polluted*. And the possibility of this type of discharge to cause some problem in the river is depicted in clauses (4) and (5), which states that given a organic polluted effluent and with no evidence of a good situation in the river, the river state will result damaged ($\neg$*good*). Finally, the intended meaning of clause (6) is that it is necessary to perform a preventive action (*i.e.* pre-treatment) such as *neutralize_pH* if the pH is very low.

Box 6.3 summarized the possible answer sets of the small implemented agent program. It is important to remind that the initial conditions for the four relevant parameters considered to describe the possible states, and for each answer set S, are

`(d(bod5_very_high, T), certain)`,
`(d(pH_very_low, T), certain)`,
`(wwtp_eff(normal, T), certain)`,
`(wt(normal_operation, T), certain)` and
`(river(good, T), certain)`,

where time T = 0.

Moreover, apart from `action(discharge, T)`, another initial action deduced from clause (6) is `action (neutralize_pH, T)`. All these initial states are part of the solutions S although we do not write them in order to gain space and make the reading of solutions more easier.

Considering the answer sets written in Box 6.3 of the program encoded in Box 6.2, it is concluded that, given an emergent industrial discharge and the initial conditions, eight possible situations in the system could exist. These are:

- the possibility to undergo either filamentous bulking, dispersed growth or biological foaming and hence to cause oxygen depletion to the river and cause a no good final river state (S_4, S_5 and S_8, respectively);
- the possibility to do not undergo a problem at the WWTP but still with the possibility of having a bad quality at the final receiving media (S_1); and finally
- the possibility to have answers with both an atom and its negation such as river(good) and ¬ river(good) (S_2, S_3, S_6 and S_7).

The solutions of the latter possibility are known as *inconsistent* answer sets. Observe that, although they are inconsistent, they contain important information *w.r.t* the considerations of our scenario. For example S_2 suggests that even though it is plausible that the WWTP operational situation can be normal after the discharge, it is also probable that the river can be polluted by the content of the effluent. Global complexes are important to disclose these situations (*e.g.* the fact that the weather situation is dry -no rainfall- for a long period, might cause a reduction of the river's dilution capacity).

In reference to the attack relations between the possibilistic arguments, for instance let us consider, in one hand, the arguments $arg10$ and $arg11$ of Box 6.4. It is clear that both arguments have complementary conclusions. In this case, we will say that the arguments $arg10$ and $arg11$ attack each other because both arguments have the same confidence degree. However, if it was the case that $arg10$ had less degree of confidence than $arg11$, $arg11$ would attack $arg10$ but not viceversa. On the other hand, how will a possibilistic argument be affected by the presence of negative literals in its support in the interaction with other possibilistic arguments? Let us consider, for example, $arg3$ of Box 6.4. We can see that $arg3$ is concluding the presence of filamentous bulking by assuming the no evidence of any other biological problem (*i.e.* dispersed growth, biological foaming). However, there are arguments as $arg8$ which have as conclusion the no evidence of filamentous bulking; hence in this case we can say that $arg8$ attacks $arg3$ (see Box 6.5 for attack relations).

Having in mind these previous ideas, it is possible to define the Argumentation Framework such as done in Box 6.6 and to apply a specific pattern of selection (*i.e.*

semantics) to finally depict the possible scenarios (see Box7). Apart form the observations written in Box 6.7, it is important to take into account that by considering the skeptical version of the preferred semantics (*i.e.* the intersection of all the preferred extensions for all the models, not only for S_3), we have the possibilistic set {`action(neturalize_pH), confirmed`} as the main conclusion of the argumentation inference. Hence a good *informed decision* in the given situation is to neutralize the pH before entering the biological reactor at the WWTP to prevent further problems.

6.5 Conclusions

The main conclusions of this chapter can be summarized as follows:

- We have proposed a knowledge-based framework useful to structure the relevant information in order to make easier and understandable the inference of new knowledge (§6.3.2). We have shown how to built *diagnoses* from the interaction of answer set programs that capture *empiriums*, *observations*, *facets* and *findings*. This knowledge has been used to define the possible states in the river basin (under the consideration of some relevant aspects).

- The relationships of these states were represented by using *finite state automata* for industries–WWTPs and WWTPs–river interactions, respectively (§6.3.1).

- The specification of these states (that is to say, the involved knowledge used by the agents) by means of ASP lead us to obtain a logic program that can be directly solved (§6.4). Therefore, the process of diagnosing the state of the river basin can be automated. Obviously, this is not the only technique that can be used to get an automated diagnosing process but, according to the work presented, it is an informed, useful and effective one for the domain under study.

- A possibilistic-based argumentation approach is proposed in order to specify the domain knowledge. We briefly explain how to build, value, find attack relations and evaluate the arguments that emerge from a concrete knowledge base. This approach is further discussed in Chapter 8.

Box 6.2. Industrial wastewater discharge *agent.*
Knowledge Base *level*[possibility label]:`atoms`

empiriums [certain]: `BOD, COD, pH, nutrients`
observation [certain]: `discharge_characteristic(pH_very_low).`
observation [certain]: `discharge_characteristic(bod5_very_high).`
finding [confirmed]: `biodegradability(ratio_BOD:COD_medium).`
finding [confirmed]: `nutrient_availability(ratio_COD:N_medium).`
facet [plausible]: `discharge_type(organic_polluted).`
facet [plausible]: `river_situation(oxygen_depletion).`
diagnose [probable]: `problem(filamentous_bulking).`
diagnose [supported]: `problem(biological_foaming).`
diagnose [supported]: `problem(dispersed_growth).`
diagnose [probable]: `river_status(poor).`
diagnose [probable]: `river_status(good).`
global complexes [confirmed]: `weather(no_rainfall).`
global complexes [confirmed]: `environmental_temperature(temperate).`

Disjunctive clauses:

(1) `wt(filamentous_bulking, T + 1) :- action(discharge, T), not wt(biological_foaming, T + 1), not wt(dispersed_growth, T + 1), not wt(normal_operation, T + 1), d(bod5_very_high, T), time (T).`

(2) `¬wt(normal_operation, T + 1) :- action(discharge, T), d(bod5_very_high, T), not wt(normal_operation, T + 1), time(T).`

(3) `wwtp_eff(organic_polluted, T + 1) :- not ¬wt(normal_operation, T + 1), d(bod5_very_high, T), action(discharge, T), time(T).`

(4) `river(oxygen_depletion, T + 2) :- wwtp_eff(organic_polluted, T + 1), not river(good, T + 2), time(T).`

(5) `¬river(good, T + 2) :- wwtp_eff(organic_polluted, T + 1), d(bod5_very_high, T), not river(good, T + 1), action(discharge, T), time(T).`

(6) `action(neutralize_pH, T):- d(pH_very_low, T), time(T).`

...

A small implementation of the industrial wastewater discharge scenario can be found in Annex B. This implementation is based on the answer set solver SMODELS (184).

Box 6.3. **Answer Sets**

S_1={(**wt(normal_operation,1),plausible**),
(¬wt(filamentous_bulking,1),probable),
(¬wt(dispersed_growth,1),supported), (¬wt(biological_foaming,1),supported),
(wwtp_eff(organic_polluted,1),plausible),
(river(oxygen_depletion,2),plausible), (¬**river(good,2),probable**)}

S_2={(**wt(normal_operation,1),plausible**),
(¬wt(filamentous_bulking,1),probable),
(¬wt(dispersed_growth,1),supported), (¬wt(biological_foaming,1),supported),
(wwtp_eff(organic_polluted,1),plausible), (**river(good,2),probable**),
(¬**river(good,2),probable**)}

S_3={(¬wt(normal_operation,1),plausible),
(**wt(filamentous_bulking,1),probable**),
(¬wt(dispersed_growth,1),supported), (¬wt(biological_foaming,1),supported),
(wwtp_eff(organic_polluted,1),plausible), (**river(good,2),probable**),
(¬**river(good,2),probable**)}

S_4={(¬wt(normal_operation,1),plausible),
(**wt(filamentous_bulking,1),probable**),
(¬wt(dispersed_growth,1),supported), (¬wt(biological_foaming,1),supported),
(wwtp_eff(organic_polluted,1),plausible),
(river(oxygen_depletion,2),probable), (¬**river(good,2),probable**)}

S_5={(¬wt(normal_operation,1),plausible),
(¬wt(filamentous_bulking,1),probable),
(**wt(dispersed_growth,1),supported**),
(¬wt(biological_foaming,1),supported),
(wwtp_eff(organic_polluted,1),plausible),
(river(oxygen_depletion,2),probable), (¬**river(good,2),probable**)}

S_6={(¬wt(normal_operation,1),plausible),
(¬wt(filamentous_bulking,1),probable),
(**wt(dispersed_growth,1),supported**),
(¬wt(biological_foaming,1),supported),
(wwtp_eff(organic_polluted,1),plausible), (**river(good,2),probable**),
(¬**river(good,2),probable**)}

S_7={(¬wt(normal_operation,1),plausible),
(¬wt(filamentous_bulking,1),probable),
(¬wt(dispersed_growth,1),supported), (**wt(biological_foaming,1),supported**),
(wwtp_eff(organic_polluted,1),plausible), (**river(good,2),probable**),
(¬**river(good,2),probable**)}

S_8={(¬wt(normal_operation,1),plausible),
(¬wt(filamentous_bulking,1),probable),
(¬wt(dispersed_growth,1),supported), (**wt(biological_foaming,1),supported**),
(wwtp_eff(organic_polluted,1),plausible),
(river(oxygen_depletion,2),probable), (¬**river(good,2),probable**)}

Box 6.4. Let us consider an instantiation of the the possibilistic logic program introduced in Box 6.2 whose possibilistic answer sets are represented in Box 6.3. Some relevant **possibilistic arguments** built from model S_3 of the presented scenario are:

argument (*arg*) = ⟨ `claim`, *support*, α ⟩

$arg1 =$ ⟨`action(neutralize_pH, 1)`,
$\{confirmed : action(neutralize\_pH, 1) \leftarrow d(pH\_very\_low, 0);$
$certain : d(pH\_very\_low, 0) \leftarrow \top\}$,confirmed⟩

$arg2 =$ ⟨`¬wt(filamentous_bulking, 1)`,
$\{plausible : \neg wt(normal\_operation, 1) \leftarrow action(discharge, 0),$
$d(bod5\_very\_high, 0), not\ wt(normal\_operation, 1);$
$certain : action(discharge, 0) \leftarrow \top;$
$certain : d(bod5\_very\_high, 0) \leftarrow \top\}$,plausible⟩

$arg3 =$ ⟨`wt(filamentous_bulking, 1)`,
$\{probable : wt(filamentous\_bulking, 1) \leftarrow action(discharge, 0),$
$\neg wt(filamentous\_bulking, 1)\ \neg wt(dispersed\_growth, 1)$
$\neg wt(normal\_operation, 1)\ certain : action(discharge, 0)$
$\leftarrow \top; certain : d(bod5\_very\_high, 0) \leftarrow \top\}$,supported⟩

$arg4 =$ ⟨`¬wt(dispersed_growth, 1)`,
$\{supported : \neg wt(dispersed\_growth, 1) \leftarrow action(discharge, 1),$
$not\, wt(dispersed\_growth, 1); certain : action(discharge, 0) \leftarrow \top$
$certain : d(bod5\_very\_high, 0) \leftarrow \top\}$,supported⟩

$arg5 =$ ⟨`wt(biological_foaming, 1)`,
$\{supported : \neg wt(biological\_foaming, 1) \leftarrow action(discharge, 1),$
$not\, wt(biological\_foaming, 1); certain : action(discharge, 0) \leftarrow \top$
$certain : d(bod5\_very\_high, 0) \leftarrow \top\}$,supported⟩

$arg6 =$ ⟨`wwtp_eff(organic_polluted, 1)`,
$\{plausible : wwtp\_eff(organic\_polluted, 1) \leftarrow action(discharge, 1),$
$not \neg wt(normal\_operation, 1)\ certain : action(discharge, 0) \leftarrow \top$
$certain : d(bod5\_very\_high, 0) \leftarrow \top\}$,plausible⟩

$arg7 =$ ⟨`wwtp_eff(organic_polluted, 1)`,
$\{plausible : wwtp\_eff(organic\_polluted, 1) \leftarrow wt(filamentous\_bulking, 1),$
$not\, wt(dispersed\_growth, 1), not\, wt(biological\_foaming, 1)$
$certain : action(discharge, 0) \leftarrow \top$
$certain : d(bod5\_very\_high, 0) \leftarrow \top\}$,supported⟩

$arg8 =$ ⟨`wwtp_eff(organic_polluted, 1)`,
$\{plausible : wwtp\_eff(organic\_polluted, 1) \leftarrow not\, wt(filamentous\_bulking, 1),$
$wt(dispersed\_growth, 1), not\, wt(biological\_foaming, 1)$
$certain : action(discharge, 0) \leftarrow \top$
$certain : d(bod5\_very\_high, 0) \leftarrow \top\}$,probable⟩

$arg9 =$ ⟨`wwtp_eff(organic_polluted, 1)`,
$\{plausible : wwtp\_eff(organic\_polluted, 1) \leftarrow not\, wt(filamentous\_bulking, 1),$
$not\, wt(dispersed\_growth, 1), wt(biological\_foaming, 1)$
$certain : action(discharge, 0) \leftarrow \top$
$certain : d(bod5\_very\_high, 0) \leftarrow \top\}$,plausible⟩

$arg10 =$ ⟨`river(good, 2)`,
$\{probable : river(good, 2) \leftarrow wwtp\_eff(organic\_polluted, 1),$
$not\, river(oxygen\_depletion, 2)\ certain : action(discharge, 0) \leftarrow \top$
$certain : d(bod5\_very\_high, 0) \leftarrow \top\}$,probable⟩

$arg11 =$ ⟨`¬river(good, 2)`,
$\{plausible : \neg river(good, 2) \leftarrow wwtp\_eff(organic\_polluted, 1),$
$not\, river(good, 1)\ certain : action(discharge, 0) \leftarrow \top$
$certain : d(bod5\_very\_high, 0) \leftarrow \top\}$,probable⟩

Observe that each possibilistic argument represent a possible conclusion by itself *w.r.t* the given scenario. Also it is important to observe that there are conclusions which are supported by more that one argument. For instance, the arguments *arg*6, *arg*7, *arg*8 and *arg*9 have as a conclusion that the WWTP effluent is organic polluted; however, these arguments have different support and different degree of uncertainty.

Box 6.5. Let us consider the possibilistic arguments of Box 6.4. By instantiating Definition 6.2, one can identify the following **conflicts** between these possibilistic arguments:

$arg2$ attacks $arg6$
$arg3$ attacks $arg8$
$arg3$ attacks $arg9$
$arg11$ attacks $arg10$
$arg10$ attacks $arg11$

Box 6.6. By considering the possibilistic arguments of Box 6.4 and the relations of attacks of these arguments identified in Box 6.5, we can construct the following **possibilistic argumentation framework**:

$AF_P = \langle\{arg1, arg2, arg3, arg4, arg5, arg6, arg7, arg8, arg9, arg10, arg11\}, \{(arg2,arg6), (arg3,arg8), (arg3,arg9), (arg10, arg11), (arg11,arg10)\}\rangle$

Box 6.7. Let P be the possibilistic program presented in Box 6.2 and AF_P be the possibilistic argumentation framework presented in Box 6.6. As we saw, AF_P can be regarded as an instantiation of P. Now, let us consider an **argumentation semantics** in order to infer conclusions from AF_P. For instance, by applying the **preferred** semantics to AF_P, we get two preferred extensions:

$E1 = \{arg1, arg2, arg3, arg4, arg5, arg7, arg10\}$

$E2 = \{arg1, arg2, arg3, arg4, arg5, arg7, arg11\}$

This means that we can infer the following two possible scenarios from P:

φ(E1)={(action(discharge, 0), confirmed),
(wwtp_eff(organic_polluted, 1), probable),
(not river(oxygen_depletion, 2), probable),
(river(good, 2), probable)}

φ(E2)={(action(discharge, 0), confirmed),
(wwtp_eff(organic_polluted, 1), confirmed),
(not river(good, 2), probable)}

Observe that both sets of possibilistic atoms are consistent. Now what can we infer from these preferred extension *w.r.t* the *river basin* scenario? First of all, we can see that there are two *independent situations* if the discharge is done. One which suggests that it is probable/supported that the river state can be good and another one which suggests that it is probable/supported that a good status cannot be present in the river if the proposed course of actions is performed.

Chapter 7

Agent-based argumentation approach for industrial wastewater discharges management

Multi-agent systems depend upon interaction between agents – no single agent has sufficient skills or resources to carry out the tasks which the multi-agent system as a whole is faced with. MAS are usually built to operate in the real world, hence the agents must deal with the usual problems of incomplete and uncertain information. Sharing information to reach a common decision is a necessity in MAS. This can be done through dialogue between agents. This dialog can be guided by the use of argumentation, a mechanism which provides a symbolic model for agent decision making (145). In this chapter a framework that allows agents to deliberate in safety critical domains, such as wastewater pollution caused by industries, is presented.

Several authors have suggested the use of argumentation techniques as the basis for negotiation and collaboration dialogues between agents (9). In §4.4.1 the informal argumentation framework based on the process of critical questioning was briefly described. The process of critical questioning could go on and on without any clearly define stopping point (207). However, to limit this, some protocols are being studied to frame this process (16). Accordingly, in §7.1.1 the *ProCLAIM* model is introduced, as well as its associated basic protocol-based exchange of arguments that frame the process of critical questioning (§7.1.2). Some relevant running examples are given *w.r.t* the problem of industrial wastewater discharges in the context of river basins.

7.1 Multi-agent argumentation-based solution approach about decision making on environmental management contexts

Argumentation is a process whereby arguments are constructed and evaluated in the light of their conflict-based interactions with other arguments. It is inherently dialectical, where the dialogue is driven by the participants' exchange of arguments. This dialectical nature of argumentation is particularly exploited by the use of AS and CQ. As described in the informal logic literature *e.g.* in (209),

- **Arguments** (*Arg*) provide the pros and cons of decisions built from knowledge bases (which are often uncertain) (8).
- **Argument Schemes** (*AS*) are forms of argument that model stereotypical patterns of reasoning (208). Within argumentation theory, argument schemes are a standard way with which to encode rules (192).
- **Critical Questions** (*CQ*) offer the user (interlocutor, analyst, evaluator, student, *etc.*) a choice among strategies for probing into the weak points in such an argument (208).

Accordingly AS are used to classify different types of argument that embody stereotypical patterns of reasoning. Instantiations of AS can be seen as providing a justification in favor of the conclusion of the argument. The instantiated scheme (what we term an *argument*) can be questioned (attacked) through posing CQs associated with the scheme. Each CQ can itself be posed as an attacking argument instantiating a particular AS. This AS is then itself subject to critical questioning. The AS and CQ effectively map out the *relevant* space of argumentation, in the sense that for any argument they identify the valid attacking arguments from amongst those that are logically possible. In that sense they provide a natural basis for structuring argumentation based dialogue protocols *e.g.* (17; 208; 210).

AS together with CQs provide a better understanding of the agent's deliberative context. They not only serve to structure arguments, but also embed a great deal of the contextual knowledge. An AS for action and its associated CQ are used as the basis for definition of a dialogue protocol (see §7.1.2).

Environmental conflicts offer good opportunities to evaluate options due to the complexity of the problems under study (101). In relation to our studied scenario, discharge protocols have many characteristics that suggest the appropriateness of multi-agent solution (205):

- they are safety critical;
- they involve large amounts of data;
- the data are diverse in source and format;
- complex inferences must be made from combination of data;
- coordinated activity across numerous agencies may be indicated; and finally,
- strong legal and ethical obligations underpin the interaction between these agencies.

Argumentation by means of AS and CQ formulation helps to explore the following dimensions of decision making: the use of relevant knowledge to understand and make decision about the problems; and the critical processing of sources of information and authority and the development of criteria for evaluating possible solution to the problem (101).

7.1.1 The *ProCLAIM* model

ProCLAIM defines a setting in which the different agents (*e.g.* those involved in the UWS management) can effectively deliberate over the safety of the proposed actions. It was first presented and used in the medical domain by Tolchinsky *et al.* (194).

Broadly construed, the *ProCLAIM* model consists of a Mediator Agent (MA), directing proponent agents (*e.g.* industries, WWTP manager, *etc.*) in an argument based collaborative decision making dialog, in which the final action should comply with certain domain dependent guidelines. However, the arguments submitted by the proponent agents may also persuade the MA to accept decisions that deviate from the guidelines. For example, the MA may be able to reason that the submitted arguments supporting an alternative decision have proven to be correct in previous similar deliberations.

Accordingly, *ProCLAIM* model is intended to assist developers in extending MAS so that these extended systems support deliberation dialogues among agents for deciding whether a proposed action is safe (it has been successfully applied for this purpose in the medical domain *e.g.* in (197)). *ProCLAIM* can be regarded as defining a centralized medium through which heterogeneous agents can effectively and efficiently deliberate. This centralized medium is embodied by the MA which role is to warrant the success of the deliberation process. In particular the MA is assigned four main tasks:

- Guide the participants as to what their legal dialectical moves are at each stage of the deliberation. In particular, what schemes they can insatiate. In this way, the deliberation can be regarded as an argumentative process for eliciting the relevant knowledge from the participants (domain experts), as opposed to defining a strategic dialogue in which a better choice of arguments may better serve the agents' individual goals.

- Decide whether or not the participants' submitted arguments are relevant for the discussion and thus, added to the graph of interacting arguments. Arguments, although may be well formed with respect to the underlying model of argumentation, may be nonsensical or too weak when contextualized in the problem at hand. The MA has to prevent these spurious arguments from disrupting the course of the deliberation.

- Submit additional arguments deemed relevant by guidelines and/or previous similar deliberation, that were not taken into account by the participants of the current deliberation. Ensuring, in this way, that all available knowledge is being accounted for, when deciding whether or not to perform a safety-critical action.

- Evaluate the submitted arguments that were accepted, in order to propose a solution. This involves resolving the symmetrical attacks between arguments into asymmetrical attacks. Once this is done, Dung's calculus of opposition is applied to identify the winning arguments. Thus, in particular, whether the proposed action can safely be performed or not.

In order to carry out these tasks, the MA employs four knowledge resources that are part of the model, depicted in Figure 7.1, and briefly described below:

Domain Consented Knowledge (DCK) Encodes the scenario's domain consented knowledge. Referenced by the MA in order to account for the domain's guidelines, regulations or any knowledge that has been commonly agreed upon.

Case-Based Reasoning component (CBRc) Stores past cases and the arguments given to justify the final decision. Referenced by the MA in order to evaluate the arguments on an evidential basis.

Argument Source Management (ASM) This component manages the confidence in the participants' knowledge on the domain. It is referenced by the MA in order to bias the strength of the arguments on the basis of the agents that endorse them.

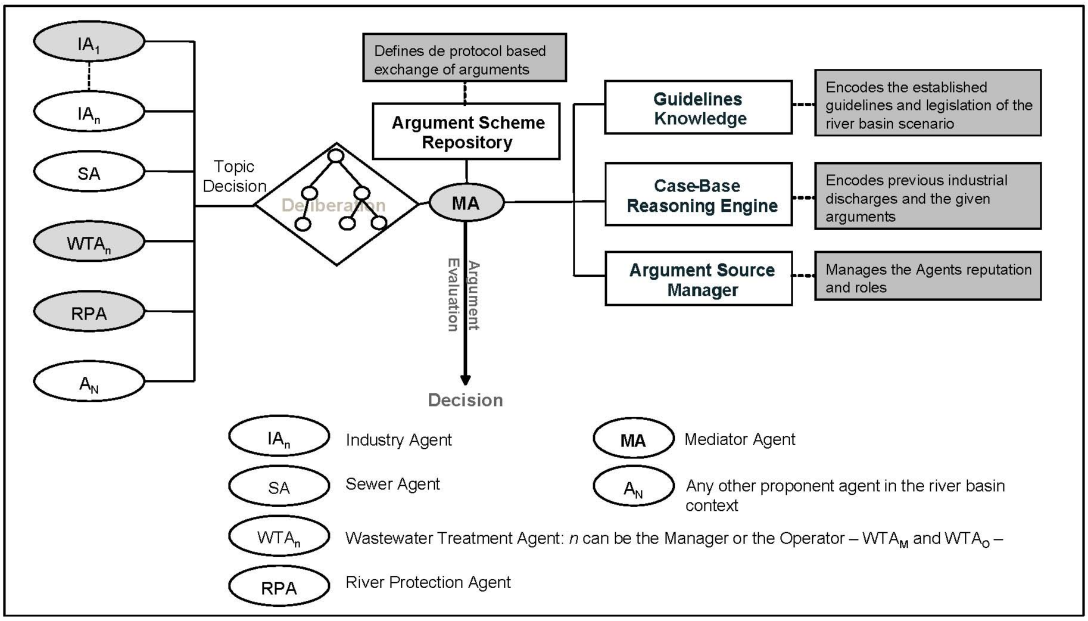


Figure 7.1: *ProCLAIM* 's architecture. Shaded boxes identify the model's constituent parts specialized for the basin scenario. Shaded ovals identify the participant agents in the example presented

ProCLAIM defines two layers of interaction. One in which agent exchange arguments (instantiated schemes) and another in which they exchange information that is potentially relevant for the deliberation. Thus, for example, agents will update each other via the *context layer* on facts such as the industrial discharge's content, the WWTP's characteristics and the climatological conditions. Whereas the argumentation will occur at the *deliberation layer*. Of course, they may be other required interaction layers for each particular scenario of application, where, for example, agents will have to negotiate to decide who does what or to persuade one another on certain issues.

A deliberation in *ProCLAIM* starts with the submission of the argument proposing the initial actions (*e.g.* discharge industrial wastewater). Further submitted argument will attack or defend the justification given for the action proposal. Each submitted argument must instantiate one of the AS in the ASR. Thus, at each stage of the deliberation the MA references the ASR in order to indicate the participants what are the schemes they can instantiate in reply to the already submitted arguments. To prevent false arguments, the MA validates each of the participants' submitted arguments against the DCK, CBRc and ASM. The MA checks that the schemes' instantiations are accepted by the consented knowledge. MA also checks if there is evidence that the submitted argument is a relevant argument and/or the agent who submitted the argument is sufficiently trustworthy to exceptionably accept an argument deemed weak by the DCK[11]. In this way, the deliberation is highly focused. Only the reasoning lines defined by the ASR are accounted for, and no spurious argument that may disrupt the course of the deliberation is taken into account.

In parallel, the participant agents update each other of the circumstances they are aware of via the *context layer*. Once the graph of interacting arguments is constructed, the MA checks whether there are any facts stated to be the case in the *context layer* that was not accounted for by the participant agents.

The agents' submitted arguments shape a graph of interacting arguments based on the *attack relation* (see, for example, Figure 7.4). The arguments used to make these graphs are those available at the ASR that had been built according the answer sets resulting from the agent's reasoning process (see §6.4) and the issues introduced in §7.1.2. For more accurate and extensive information about the model refer to (58; 197).

7.1.2 *ProCLAIM* 's basic protocol-based exchange of arguments

The ASR is based on one AS for action proposal from which the protocol for the exchange of arguments is defined as follows:

An argument is represented as a 5-tuple[12]:

$$<\textit{Context, Fact, Prop\_Action, Effect, Neg\_Goal}>$$

where **Context** (C) is a set of facts that are not under dispute, that is, assumed to be true. **Fact** R is a set of facts such that given the context C, then the proposed action (or set of actions) **Prop_Action** (A) result in a set of states **Effect** S that realizes some

[11]Suppose a trustworthy agent submits an argument A proposing an alternative action to warrant the safety of the initially proposed action. Both, the DCK and CBRc may deem A too weak to be accepted. However, because the agent is trustworthy, argument A may exceptionally be accepted. That is, added to the graph of interacting arguments.

[12]This basic argument scheme is based on Atkinson's schemes for action proposal (16).

undesirable goal **Neg_Goal** (G^-). *Fact* and *Effect* may be empty sets and *Neg_Goal* may be equal to `nil`, representing that no undesirable goal is realized. So, arguments in favor of a proposed action are of the form: $<$*Context, Fact, Prop_Action, Effect,* `nil`$>$ whereas arguments against a proposed action, for instance against an industrial spill, highlight some negative goal that will be realized *e.g.* $<$*Context, Fact, Prop_Action, Effect,* `fauna_death`$>$.

Hence, the arguments used in the dialogue take into account:

- **R**: the current state of affairs referenced by the facts deemed relevant by the proponent agents;
- **A**: the set of possible actions;
- **S**: the new state achieved if a proposed action is undertaken, that is, the set of side effects that an industrial discharge may cause;
- **G**$^-$: the undesirable goals which the new state realizes.

It is now possible to reformulate the problem of deciding whether an industrial wastewater discharge is environmentally safe as a process of identifying which are the relevant facts in the current circumstances (r_1,..., r_n in R) because of which the wastewater discharge, along with other complementary actions (a_1,..., a_n in A), cause or not any side effect s_1 in S, that realizes an undesirable goal g_1 which justifies not performing the course of actions a_1,..., a_n. Figure 7.2 graphically depicts an example of the formation of an argument by means of linking the pieces of information organized as R, A, S and G^-. These arguments can announce either an undesirable goal (*argument con*) or a favorable one (*argument pro*).

Thus, to argue *against* an industrial discharge means to indicate that there is a subset of R from which the proposed actions will cause a side effect that realizes some undesirable goal. For example the argument:

> The industrial discharge contains a concentration of *readily biodegradable organic matter -rbCOD-* that will cause an *overgrowth of filamentous bacteria* causing *filamentous bulking.*

An argument defending the discharge's safety, will contradict such statement. For example the argument:

> The industrial discharge that contains a concentration of *rbCOD* will not cause the side effect *overgrowth of filamentous bacteria* achieving the undesirable goal *filamentous bulking* since the action *add nutrients* can be

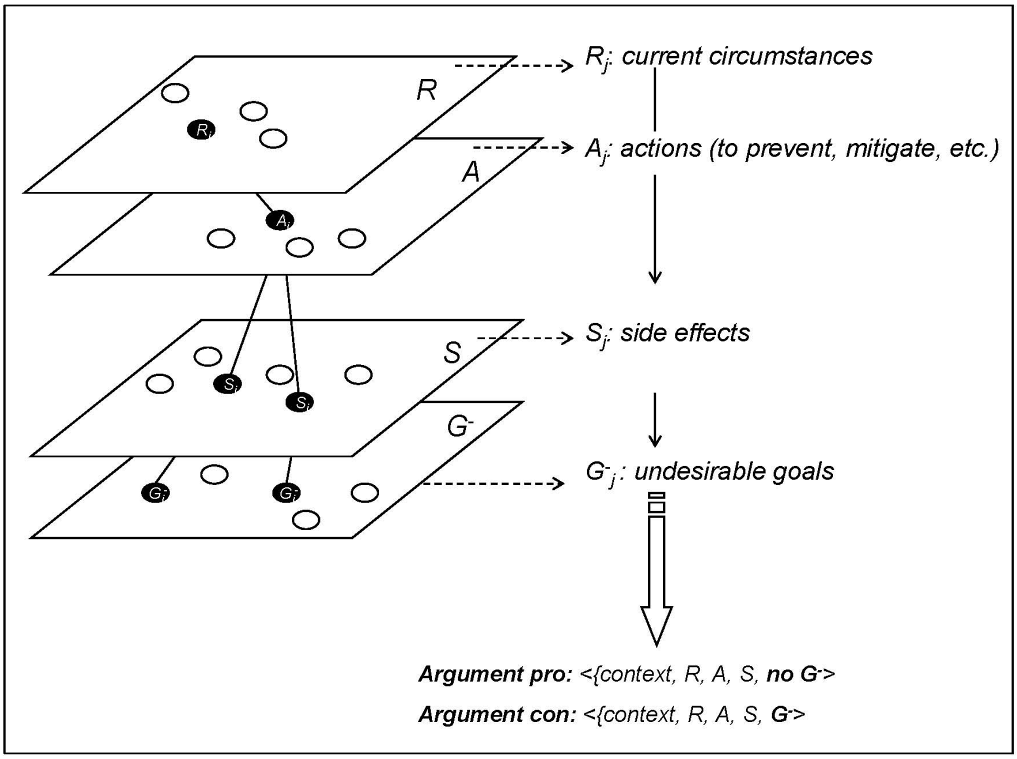


Figure 7.2: Argument formation using as a basis a set of R, A, S and G^{-}

performed to avoid the side effect *overgrowth of filamentous bacteria* and thus, prevent *filamentous bulking*.

Therefore typical problems such as *filamentous bulking* can be rephrased in terms of interaction of these arguments constructed instantiating the tuple R, A, S and G. This tuple, in fact, defines an Argument Scheme (AS). Table 7.1 summarizes a subset of possible values of **R**, **A**, **S** and $\mathbf{G}^-$.

Once the AS are identified, *ProCLAIM* defines an argumentative process formalized in terms of a structured set of AS and CQ. These AS and CQs conform a protocol-based exchange of arguments (see Figure 7.3), that allows identifying which arguments can be submitted at each stage of the deliberation. This protocol is used by the MA in order to guide the participant agents in their argument submission. Through this guidance, participant agents (experts) are led to unfold the relevant facts in R and complementary actions in A and indicate why they are relevant for the decision making.

In *ProCLAIM*, a proposed action (*e.g.* discharge industrial wastewater) is deemed to be appropriate if there are no expected undesirable side effects. Thus, a proposed action is by default assumed appropriate. Nonetheless, there must be some minimum set of conditions for proposing such an action (*e.g.* an industry with wastewater, and a receiving media). Thus, the dialogue starts by submitting an argument that claims the appropriateness of an action and the subsequent dialogue moves will attack or defend the presumptions present in that argument by claiming there is (*resp.* there is not) an undesirable side effect.

The six schemes we now introduce are partial instantiation of the more general scheme previously introduced. These more specific schemes are intended to identify the legal instantiation of the more general scheme at each stage of the dialogue.

A dialogue starts with the submission of the argument:

AS1 $\langle m\_c, \{\}, p\_a, \{\}, \texttt{nil} \rangle$ where $m\_c \in R$ is a minimum set of facts that an agent requires for proposing a nonempty set of actions $p\_a \in A$. An argument proposing an action (via AS1) can be attacked via the argument scheme AS2, which is elicited from posing CQ1.

> **AS1_CQ1**: Is there a contraindication for performing the proposed action?

AS2 introduces a new set of facts, deemed to be a contraindication (*e.g.* a certain toxic in the spill), and thus, attacks the proposed action appropriateness, `proposed_actions`.

Table 7.1: Sets of information used to construct arguments

	Notation	Description
Initial States (R)	r1:ind_ww(COD)	Industrial wastewater concentration of COD
	r_2:ind_ww(N, P)	Industrial wastewater concentration of nutrients (N and P)
	r_3:ind_ww(BOD)	Industrial wastewater concentration of BOD
	r_4:ind_ww(Cd)	Industrial wastewater concentration of cadmium (Cd)
	r_5:ind_ww(Cr)	Industrial wastewater concentration of chromium (Cr)
	r_6:fungi	Presence of fungi spp. in the active biomass (*e.g. Pseudomonas sp.*, *Aspergillus sp.*, *Candida maltosa*, *etc.*)
	...	...
	r_{10}:WWTP_design	WWTP design parameters (desirable maximum flow, N/D capacity, type of reactor...)
	r_n: ...	...
Actions (A)	a_1:add_nutrients	Add nutrients (N or P) to prevent negative effects
	a_2:increase_WAS	Increase WAS to modify WWTP performance
	a_3:add_coag	Add coagulants/flocculants to prevent or mitigate negative effects
	a_4:NN^+_reactors	Favor nitrification in reactors through a set of interrelated actions.
	a_5:DN^-_clarifiers	Avoid denitrification in clarifiers through a set of interrelated actions.
	a_6:NN^-_reactors	Avoid nitrification in reactors through a set of interrelated actions.
	a_n:...	...
Final States (S)	s_1:fil.B-(type)	Inhibition of filamentous bacteria
	s_2:fil.B+(type)	Overgrowth of filamentous bacteria
	s_3:NN/DN	Encouragement of nitrification/denitrification processes
	s_4:DO_depletion	Depletion of available DO
	s_5:hydraulic.shock	Hydraulic shock at the WWTP due to a heavy rain or storm
	s_6:overdose	Overdose application of coagulants/flocculants
	s_7:toxic_sludge	Presence of toxics within the sludge
	s_n:...	...
Undesirable Goals (G^-)	g_1:fil.bulking	Overgrowth of filamentous bacteria
	g_2:viscous.bulking	Excessive productions of EPS by the floc-forming bacteria (viscous sludge is difficult to settle and become compact)
	g_3:bio.foaming	Overgrowing of Foam-forming filamentous bacteria
	g_4:dispersed.growth	The absence of EPS hinders the formation of flocs
	g_5:rising	Denitrification occurs in clarifiers (instead of in reactors)
	g_6:pin-point floc	The absence of filaments hinders the formation of large flocs
	g_7:biomass.loss	Washout of biomass hence loss of active microorganisms
	g_8:aquatic.toxicity	Toxicity to aquatic organisms of WWTP effluent water with overdose of coagulants/flocculants
	g_9:charge.reversal	Overdose of coagulants/flocculants can cause a complete charge reversal and re-stabilize the colloid complex, thus settling problems
	g_{10}:sludge.toxicity	Accumulation of toxic substances in the sludge, making them unavailable for posterior uses (*e.g.* compost for agriculture)
	g_n:...	...

Note: COD (Chemical Oxygen Demand), BOD (Biochemical Oxygen Demand), N (nitrogen), P (Phosphorous), N/D(nitrification/denitrification), WAS (Waste Activated Sludge), RAS (Recycle Activated Sludge), DO (Dissolved Oxygen), CHL (Chlorine), EPS (Extracellular Polymeric Substances)

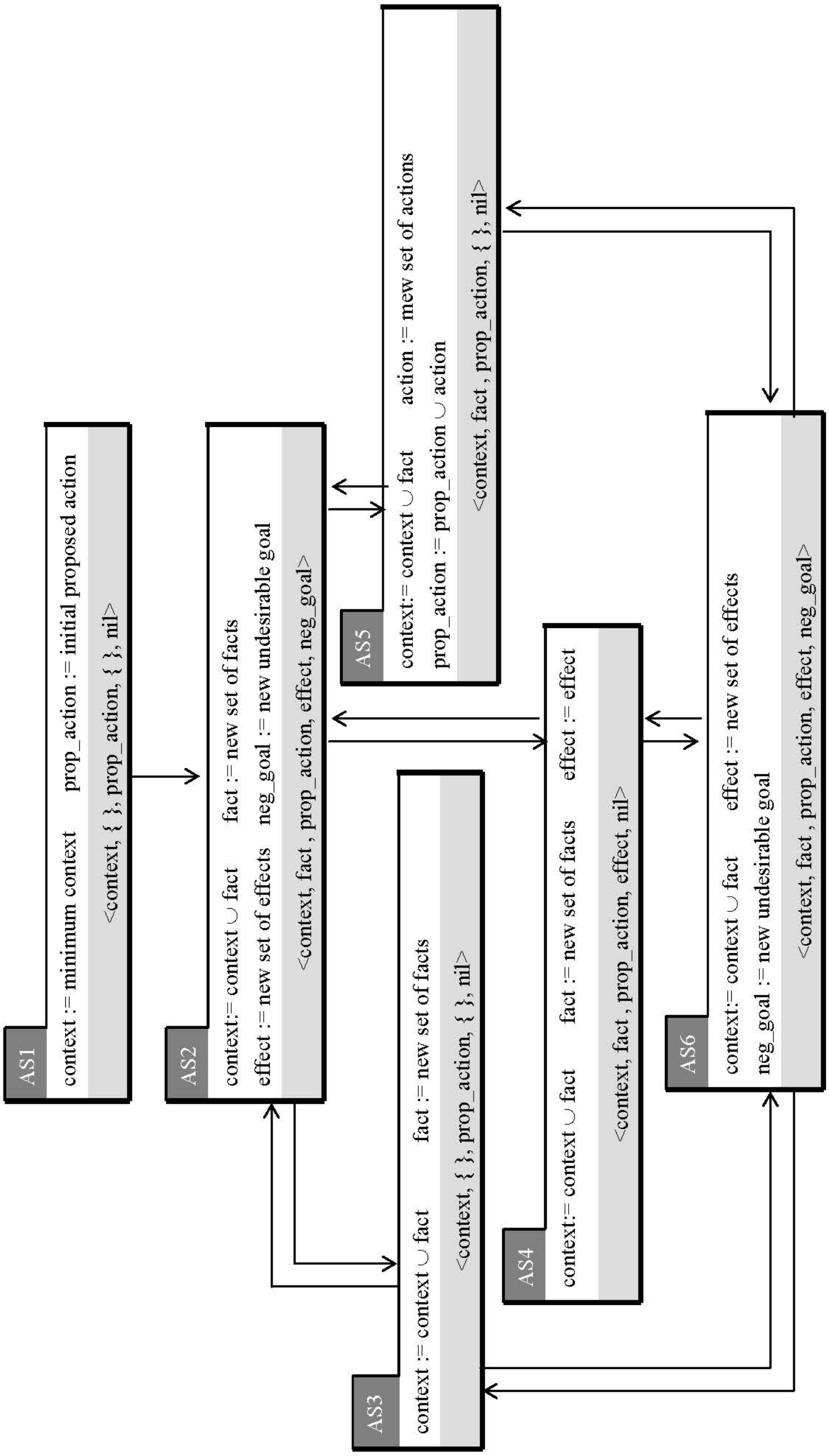


Figure 7.3: Schematic representation of the dialogue game. Adapted from Atkinson *et al.* (17)

To defend the initial proposed action, an argument instantiating AS2 can in turn be attacked by either AS3, AS4 or AS5.

> **AS2_CQ1**: Are the current circumstances such that the stated effect will not be achieved?
>
> **AS2_CQ2**: Are the current circumstances such that the achieved effect S will not realize the stated goal G?
>
> **AS2_CQ3**: Is there a complementary course of action that prevents the achievement of the stated effect S?

These schemes respectively stand for:

AS3 Current circumstances are such that the introduced set of facts fact, via scheme AS2, will not result in the stated set of effects `effect` that realize the undesirable goal `neg_goal`.

AS4 current circumstances are such that the stated set of effects `effect` does not realise the stated undesirable goal `neg_goal`.

AS5 a complementary set of actions can be undertaken in order to prevent the stated undesirable set of effects `effect`.

Finally to **AS6** can be associated the same CQs as to **AS2**. Figure 7.3 illustrates the schemes' structure and interaction.

7.2 Argument scheme repository to argue over the safety of industrial wastewater discharges

In Chapter 5 we identified the roles and agents (agent model) present in our scenario, and the the control of information and communication flows (service and acquaintances model). Inhere we show how these agents can take part in a deliberation process to deal with industrial wastewater discharges pollution. *Why paying special attention to industrial wastewater discharges?*. Because,

- for most of sanitation systems, the part of industrial effluent is simply drowned in the mass of domestic effluent, and its particularities not taken in account in the design of the treatment plant.

- among the various sources of pollution, the industrial effluent is maybe the most difficult to assess, but also the most hazardous in term of safety and steadiness of treatment performances.

A characteristic of industrial pollutant is that they may arrive at the plant in great concentration during a short period of time. Therefore, even if quantities are relatively small, they are liable to do harm by their irregularity. It is important that local authorities, WWTP managers and technical operators of the system know the location of all sewers outlets as well as the composition of effluents collected and piped to the WWTP.

In order to build the Argument Schemes a relation between the possible problems (see Figure 2.3) and their causes must be found. To sum up, the most relevant possible causes and risks related to industrial discharges' content are:

- *Toxic substances* that may damage the biological process and therefore the possibility of wastewater reuse, leading to *toxic shock* situation.
- *Heavy metals* that finally are concentrated in the sludge and prevent it for agricultural reuse.
- *High conductivity*, leading to a *conductivity shock*.
- Excessive concentration of *nutrients* (principally nitrogen and phosphorous), leading to a *nutrient shock*.
- Excessive concentration of *biodegradable organic components*, leading to an *organic shock*.
- Excessive concentration of *grease and oil* that enhance the *organic shock* situation.
- Excessive concentration of *solids*, that can lead, among other problematic situations, to *organic shock*.

Tchobanoglous in (189) list the principal constituents of concern in wastewater treatment (see Table 7.2). Note that most of them are constituents of industrial wastewater discharges.

Accordingly we are going to describe the most relevant deliberation examples *w.r.t* to the abovementioned causes-effects problematic situations, that is, the the toxic shock situation (§7.2.1) and the overloading situations (§7.2.2 and §7.2.3 for organic shock and nutrient shock, respectively).

Table 7.2: Principal constituents of concern in wastewater treatment (189)

Constituent	**Reason for importance**
Suspended Solids	SS can lead to the development of sludge deposits and anaeorbic conditions when untreated wastewater is discharged to aquatic environment
Biodegradable organics	Composed principally of proteins, carbohydrates and fats, biodegradable organics are measured most commonly in terms of BOD and COD. If discharged untreated to the environment, their biological stabilization can lead to the depletion of natural oxygen sources and to the development of septic conditions
Pathogens	Communicable diseases can be transmitted by the pathogenic organisms that may be present in wastewater
Nutrients	Both N and P, along with carbon, are essential nutrients for growth. When discharged to the aquatic environment, these nutrients can lead to the growth of undesirable aquatic life. When discharged in excessive amounts on land, they can also lead to the pollution of groundwater
Priority pollutants	Organic and inorganic compounds selected on the basis of their known or suspected carcinogenicity, mutagenicity, teratogenicity, or high acute toxicity. Many of these compounds are found in wastewater
Refractory organics	These organics tend to resist conventional methods of wastewater treatment. Typical examples include surfactants, phenols, and agricultural pesticides
Heavy metals	Are usually added to ww from commercial and industrial activities and may havet to be removed if the wastewater is to be reused
Dissolved inorganics	Inorganic constituents such as calcium, sodium and sulfate are added to the original domestic water supply as a result of water use and may have to be removed if the wastewater is to be reused

7.2.1 Toxic substances example

There is a large variety of toxic substances and their affectation to the treatment process is very different depending on the characteristics of the toxic. However, one important effect of toxic substances is that they can interrupt floc formation and produce deflocculation (*e.g.* dispersed-growth).

Accordingly, there is an industrial wastewater discharge received by a WWTP. The wastewater contain a toxic substance `T`, consequently WTA believes that the toxic can cause severe effects to the activated sludge (*e.g.* inhibition of EPS synthesis, diminution of flocs sedimentation, *etc.*). However, if there is presence of a toxic in the influent it is important to test (through respirometries) oxygen demand in order to know if the toxic is still present or not. If the results of the test show a low oxygen demand is a sign that the toxic is still entering the system. In this case, WTA_O recommends to increase the WAS rate for approximately one week to purge the system. WTA advises that when purging too much F:M ratio will increase together with a decreasing of SRT. Hence new problems, such as growth of filamentous bacteria that cause bulking can appear. If the wastewater contain high concentration of rbCOD then the F:M ratio can be balanced; the same balance can be obtained adding an external source of RBOM.

The known facts are:

- there is an industrial wastewater discharge `ind_ww`
- `wwtp` is the receiver of the discharge
- the discharge has *toxics* content
- the 'current' state of the plant is known (by the WTA) thanks the availability of a supervisory system (the so called ATL; see Chapter 5)
- the presence of toxics can cause EPS inhibition and/or diminution of flocs' sedimentation.

The conflict is:

- IA: the discharge can be done safety.
  JUSTIFICATION: it complies with legislation.
- WTA: the presence of the toxic `T` is a contraindication.
  JUSTIFICATION: because of the toxic `T` EPS can be inhibited and overcome dispersed growth.

- WTA_O: some actions can be done to prevent EPS inhibition (*e.g.* increase WAS). JUSTIFICATION: increasing the WAS rate for approximately one week the system is purged and toxics can be released from the system.
- WTA: if the purge is not done properly the ratio F:M will increase. JUSTIFICATION: the increase of F:M ratio (together with the decreasing of SRT) can origin the abnormal growth of filamentous bacteria causing of bulking.
- WTA_O: F:M ratio can be balanced. JUSTIFICATION: if wastewater contain rbCOD the ratio is balanced, otherwise it can be added an external source of RBOM to reach the same balance.

Let us suppose that an industry, represented by its IA, propose the abovementioned wastewater discharge claiming that after it no undesirable effects will occur. Accordingly, IA poses argument $Arg1$:

> **Arg1**: In the current circumstances (*i.e.* a wastewater discharge and a WWTP) industry $\mathtt{Ind}_i$ will effectuate the discharge (action $\mathtt{a}_0$) claiming that this action ($\mathtt{a}_0$) will not cause any side effect S so any undesirable goal g to the treatment system.

Generally speaking, when an industry agent (IA) claims to discharge its wastewater because no negative effects occur (*e.g.* $Arg1$), a CQ that will naturally arise is *AS1_CQ1: is there a contraindication for undertaking the proposed action?* This will help the MA to check if the following dialog move is legal. Assuming that *WTA* **knows** that the discharge contains *Chromium VI* and **believes** *Chromium VI* is a contraindication for the treatment process because there is evidence it can provoke both inhibition of nitrification (*i.e.* decreasing significantly the ammonia removal efficiency) and reduction of filaments abundance causing the appearance of pin-point floc and free-dispersed bacteria (7; 171), *WTA* reports the latter possibility by submitting $Arg2$:

> **Arg2**: If in current circumstances industry $\mathtt{Ind}_i$ effectuate the discharge ($\mathtt{a}_0$) containing Chromium VI ($\mathtt{r}_5$), this will reduce filaments abundance ($\mathtt{s}_1$) and hence provoke the appearance of pin-point flocs ($\mathtt{g}_6$).

Arg2 introduces new important information about the discharge (*i.e.* the discharge contains chromium that can cause filamentous bacteria inhibition). Different experts on the domain can naturally start a dialogue of attacking and supporting arguments, seeking for more information, for alternative actions, *etc.* to finally decide on the possible actions to be taken to prevent WWTP problems.

Up-to-date information has been documented that the degree of inhibition in activated sludge is influenced by several factors such as pH, the concentration of inhibitor, the present species, the suspended solids concentration, the sludge age, the solubility of the inhibitor and the concentration of other present cations and molecules (7; 171). According to this other possible existing counterarguments risen by three new CQs (they are meant to limit the possible counterarguments, discarding the ones that are not relevant for the discussion so looking for the key information):

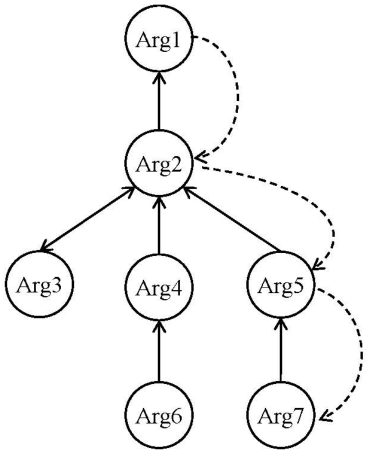
AS2_CQ1: *Are the current circumstances such that the stated effect will be achieved?* That is equivalent, in the presented example, to question if the concentration of chromium, given the current circumstances, is enough to produce the undesirable effect (*i.e.* filamentous bacteria inhibition) even if it is under legal thresholds.

AS2_CQ2: *Are the current circumstances such that the achieved effect will realize the stated negative goal?* That is, to explore other relevant circumstances in the context that makes the negative goal nil (*e.g.* synergetic effects with other pollutants, precipitation of this heavy metal due to the presence of a specific cation, *etc.*).

AS2_CQ3: *Is there a course of action that prevents the achievement of the stated effect*, that is, to explore the possible actions that can prevent or mitigate the negative effect (*e.g.* try to precipitate the heavy metal, increase the capacity of the activated sludge to adsorb heavy metals by means of some added adsorbent, *etc.*).

Figure 7.4 shows some of the possible lines of reasoning when dealing with the industrial discharge containing a heavy metal (*e.g.* chromium VI). Following the example, **AS2_CQ1**, **AS2_CQ2** and **AS2_CQ3** pose an attack to **Arg2**; consequently **Arg3**, **Arg4** and **Arg5** (see the table in Figure 7.4) attack **Arg2** (*e.g.* they are instances with new information about the discharge, possible synergetic effects of the current circumstances or an alternative action, respectively).

Arg3: If in current circumstances industry $\mathtt{Ind}_i$ effectuate the discharge ($\mathtt{a}_0$) containing Chromium VI ($\mathtt{r}_5$) it will not cause as much as necessary inhibition of filamentous bacteria ($\mathtt{s}_1$), hence does not provoke pin-point ($\mathtt{g}_6$).



ID	Argument	Proponent Agent
Arg1	<R(ww, wwtp), A(a_0), S( ), G^-(nil)>	IA
Arg2	<R(ww(r_5), wwtp), A(a_0), S(s_1), G^-(g_6)>	WTA
Arg3	<R(ww(r_5), wwtp, challenge_load), A(a_0), S( ), G^-( )>	IA
Arg4	<R(ww(r_5), wwtp(r_6)), A(a_0), S( ), G^-( )>	WTA_O
Arg5	<R(ww(r_5), wwtp(r_6)), A($a_0 \cup a_3$), S( ), G^-(nil)>	WTA_M
Arg6	<R(ww(r_5), wwtp(r_6)), A(a_0), S(s_7), G^-(g_{10})>	RPA
Arg7	<R(ww(r_5), wwtp(r_6)), A(a_0 , a_3), S( ), G^-(g_{10})>	RPA

Attack relation ⟶
Dialogue move - - - - - ->

Figure 7.4: Argument graph that captures the moves in a dialog over the acceptability of a toxic industrial discharge into the WWTP. Each node of the tree holds one argument described in the table. Each new introduced factor is highlighted.

Arg4: If in current circumstances industry $\texttt{Ind}_i$ effectuate the discharge (a_0) containing Chromium VI (r_5) it will not cause inhibition of filamentous bacteria (s_1), hence does not provoke pin-point (g_6) due to the positive present condition of activated biomass to reduce chromium VI (*i.e.* the presence of several fungi (r_6) species capable of reducing Chromium VI to a less unsafety form of this heavy metal -Chromium III- together with the availability of organic matter).

Arg5: If in current circumstances industry $\texttt{Ind}_i$ effectuate the discharge (a_0) containing Chromium (r_5) it will not cause inhibition of filamentous bacteria (s_1), hence does not provoke pin-point (g_6) since it can be added a ion (a_3) (*e.g.* ferrous) to precipitate Chromium VI.

As mentioned before, Arg3, Arg4 and Arg5 are instantiations of AS3,4,5, respectively, introducing new facts, new information about the current situation or alternative/preventive actions. These may in turn warrant or cause some undesirable secondary effect(s). Consequently, associated with these arguments an important new CQ arise leading to **Arg6** and **Arg7** instances:

AS3,4,5_CQ1: *Will the introduced factor cause some undesirable side effects?*

Arg6: If in current circumstances, industry $\mathtt{Ind}_i$ effectuate the discharge ($\mathtt{a}_0$) containing Chromium VI ($\mathtt{r}_5$), the presence of specific active biomass ($\mathtt{r}_6$) can reduce its toxicity, hence prevent pin-point ($\mathtt{g}_6$); however, the new form of chromium (Chromium III) will remain in the sludge.

Arg7: If in current circumstances, industry $\mathtt{Ind}_i$ effectuate the discharge ($\mathtt{a}_0$) containing Chromium VI ($\mathtt{r}_5$), the enhancement of chromium precipitation will prevent pin-point ($\mathtt{g}_6$); however, the precipitate will remain in settled sludge ($\mathtt{s}_7$) making them unavailable for other uses, such as in agriculture ($\mathtt{g}_{10}$), after being processed in the sludge line.

In this fashion all possible lines of reasoning *w.r.t* to the discharge and its consequences can be effectively studied, if not questioned.

Once the argument graph is constructed the MA has to determine which the *winning* arguments are. In this example (see Figure 7.4) we are going to consider the following: there is no evidence posed by any of the participant agents, that the stated *Chromium VI* load is safety, thus the line of reasoning on the left of the argument graph is discarded. Therefore, the conflict between **Arg4** and **Arg6** needs to be solved, that is, whether the current state of the plant cause positive synergetic effects to mitigate the problem. A similar procedure should be started to resolve the conflict between **Arg5** and **Arg7**. On the basis of the domain consented knowledge (articulate in terms of R, A, S and G) and the reputation of the agents involved, different strengths can be given to each of the arguments in order to finally decide which is the *winner* and which course of action is the safest for the actual WWTP performance.

Accordingly, an expert operator of the WWTP (WTA_O) holds with **Arg4** since it *reports* the presence of specific biomass that can reduce the most toxic form of chromium to a less unsafe form. However, as depicted in Figure 7.5, in critically safety decisions WTA_M has higher reputation and their arguments are ranked better than WTA_O's ones. So the reasoning line containing Arg5 is preferable.

For this specific case, and without considering past experiences, the discharge is considered unsafe. Although a mitigating action can avoid operational problems at the WWTP (*e.g.* sludge settling problems due to pin-point flocs), **Arg7** attacks **Arg5**, so finally supporting **Arg2**, certifying the unsafety of the discharge given the present conditions.

From now, since the discharge proposed by the IA should be rejected for the present circumstances, another course of action needs to be considered to manage the discharge (*e.g.* specific pre-treatment at industry, store the discharge -if storage tanks available-

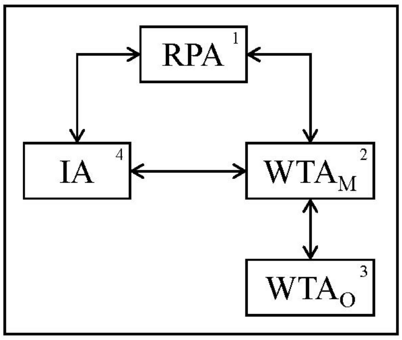


Figure 7.5: Acquaintances of agents and reputation (indicated by the numbers inside the boxes) in the proposed scenario (*i.e.* industrial discharge containing a heavy metal)

until the system is in proper conditions to hold the discharge, and/or any other possible action that could increase the argument graph for this specific problem). Moreover, since the action proposed by the IA is rejected and considering it claimed safety, its reliability (in terms of the notion of reputation) will diminish.

7.2.2 Organic matter example

Biodegradable organics are measured most commonly in terms of BOD and COD (rbBOD and rbCOD, respectively) and are principally composed of proteins, carbohydrates and fats. If the wastewater discharged into the system contain a high load of rbCOD or rbBOD several outcomes can appear:

- the process efficiency is affected, given that part of the sludge that should have been used in the treatment process is removed;
- the concentration of RAS and WAS (return and waste sludge, respectively) is very poor with negative consequences both on the control of sludge concentration in reaction basins and on the sludge dewaterability process during sludge-handling operations;
- if discharged untreated to the environment, their biological stabilization can lead to the depletion of natural oxygen sources and to the development of septic conditions.

Accordingly, there is an industrial wastewater discharge received by a WWTP. The wastewater contain rbCOD, consequently the WTA believes that rbCOD can cause filamentous bulking. However, if there is enough nutrients (N and/or P) the high quantity of rbCOD can be removed and the discharge can be performed safely.

The known facts are:

- there is an industrial wastewater discharge `ind_ww`
- `wwtp` is the receiver of the discharge
- the discharge has *rbCOD* content
- the 'current' state of the plant is known (by the WTA) thanks the availability of a supervisory system (ATL).

The conflict is:

- IA: the discharge can be done safety
  JUSTIFICATION: it complies with legislation
- WTA: the rbCOD content is a contraindication
  JUSTIFICATION: because of the content of rbCOD there will be an undesirable proliferation of filamentous bulking bacteria
- WTA_O: preventive and/or compensative action (*e.g.* add N and/or P) can be performed to avoid bulking
  JUSTIFICATION: if there is enough nutrients the quantity of rbCOD can be removed.

Let us suppose that an industry, represented by its IA, propose the abovementioned wastewater discharge claiming that after it no undesirable effects will occur. Accordingly, IA poses argument $Arg1$:

> **Arg1**: In the current circumstances (*i.e.* a wastewater discharge and a WWTP) industry $\texttt{Ind}_i$ will effectuate the discharge (action $\texttt{a}_0$) claiming that this action ($\texttt{a}_0$) will not cause any side effect S so any undesirable goal G^- to the treatment system.

When an industry agent (IA) claims to discharge its wastewater because no negative effects occur (*e.g.* $Arg1$), a CQ that will naturally arise is: *AS1_CQ1: is there a contraindication for undertaking the proposed action?* This will help the MA to check if the following dialog move is legal. Assuming that WTA **knows** that the discharge contains a high content of *rbCOD* and **believes** *rbCOD* is a contraindication for the treatment process because there is evidence it can provoke an undesirable proliferation of filamentous bulking bacteria (52), *WTA* reports the latter possibility by submitting *Arg*2:

> **Arg2**: If in current circumstances industry $\mathtt{Ind}_i$ effectuate the discharge ($\mathtt{a}_0$) containing a high concentration of rbCOD ($\mathtt{r}_1$), this will increase filamentous bacteria ($\mathtt{s}_2$) and hence provoke the appearance of filamentous bulking ($\mathtt{g}_1$).

Arg2 introduces new important information about the discharge (*i.e.* the discharge contains excessive content of organic matter that can cause filamentous bacteria excessive growth). By applying the *ProCLAIM* framework and the arguments' protocol game, different experts are encouraged to start a dialogue of attacking and supporting arguments, in order to decide on the possible actions to be taken to prevent or avoid WWTP problems.

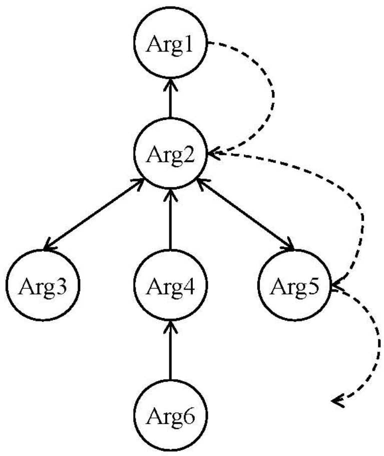
Up to date, it has been documented that large contents of soluble organic matter demand relatively large quantities of nutrients (P and N) in order to completely remove the excessive amount of rbCOD (96). According to this, other possible counterarguments exist risen by three critical questions (see Figure 7.3):

> **AS2_CQ1**: *Are the current circumstances such that the stated effect will be achieved?* That is equivalent, in the presented example, to question if the concentration of rbCOD, given the current circumstances, is enough to produce the undesirable effect (*i.e. filamentous bacteria* excessive growth) even if it is under legal thresholds.

> **AS2_CQ2**: *Are the current circumstances such that the achieved effect will realise the stated negative goal?* That is, to explore other relevant circumstances in the context that makes the negative goal nil (*e.g.* synergetic effects with other substances, *etc.*).

> **AS2_CQ3**: *Is there a course of action that prevents the achievement of the stated effect*, that is, to explore the possible actions that can prevent or mitigate the negative effect (*e.g.* try to reduce the quantity of rbCOD by adding nutrients if necessary, or by increasing WAS, *etc.*).

Figure 7.6 shows some of the possible lines or reasoning when dealing with the industrial discharge containing a high content of organic matter (*e.g.* measured as



ID	Argument	Proponent Agent
Arg1	$\langle R(ww, wwtp), A(a_0), S(\ ), G^{-}(nil)\rangle$	IA
Arg2	$\langle R(ww(r_1), wwtp), A(a_0), S(\mathbf{s_2}), G^{-}(\mathbf{g_1})\rangle$	WTA
Arg3	$\langle R(ww(r_1), wwtp(\mathbf{r_2})), A(a_0), S(\ ), G^{-}(nil)\rangle$	IA
Arg4	$\langle R(ww(r_1), wwtp), A(a_0 \cup \mathbf{a_1}), S(\ ), G^{-}(nil)\rangle$	WTA_M
Arg5	$\langle R(ww(r_1), wwtp), A(a_0 \cup \mathbf{a_2}), S(\ ), G^{-}(nil)\rangle$	WTA_O
Arg6	$\langle R(ww(r_1), wwtp), A(a_0 \cup a_1), S(\mathbf{s_3}), G^{-}(\mathbf{g_5})\rangle$	WTA_O

Attack relation	⟶
Dialogue move	- - - - ->

Figure 7.6: Argument graph that captures the moves in a dialog over the acceptability of an organic matter overload discharge into the WWTP. Each node of the tree holds one argument described in the table. Each new introduced factor is highlighted.

rbCOD). Following the example, **AS2_CQ1** and **AS2_CQ3** pose an attack to **Arg2**; consequently **Arg3**, **Arg4** and **Arg5** (see the table in Figure 7.6) attack **Arg2** (*e.g.* they are instances with new information about the discharge, or alternative actions, respectively):

> **Arg3**: If in current circumstances industry $\texttt{Ind}_i$ effectuate the discharge ($\texttt{a}_0$) containing high content of rbCOD ($\texttt{r}_1$) it will not cause as much as necessary excessive growth of *filamentous bacteria* ($\texttt{s}_2$), hence does not provoke filamentous bulking ($\texttt{g}_1$) due to the positive present condition of enough nutrients ($\texttt{r}_2$) needed to remove the excessive content of rbCOD.

> **Arg4**: If in current circumstances industry $\texttt{Ind}_i$ effectuate the discharge ($\texttt{a}_0$) containing high content of rbCOD ($\texttt{r}_1$) it will not cause as much as necessary excessive growth of *filamentous bacteria* ($\texttt{s}_2$), since nutrients can be added ($\texttt{a}_1$) (*e.g.* nitrogen) to allow the removal of excessive rbCOD.

> **Arg5**: If in current circumstances industry $\texttt{Ind}_i$ effectuate the discharge ($\texttt{a}_0$) containing high content of rbCOD ($\texttt{r}_1$) it can cause excessive growth of *filamentous bacteria* ($\texttt{s}_2$); however, the removal of Waste Activated Sludge (WAS) can be increased ($\texttt{a}_2$) in order to reduce the quantity of *filamentous bacteria*, hence to not undergo *filamentous bulking* ($\texttt{g}_1$).

As mentioned before, **Arg3**, **Arg4** and **Arg5** are instantiations of AS3,5, respectively, introducing new information about the current situation or alternative/preventive actions. These may in turn warrant or cause some undesirable secondary effect(s). Consequently, associated with these arguments an important new CQ arise leading to **Arg6** instance:

> **AS4_CQ1**: *Will the introduced factor cause some undesirable side effects?*
>
> **Arg6**: If in current circumstances, industry $\texttt{Ind}_i$ effectuate the discharge ($\texttt{a}_0$) containing high content of rbCOD ($\texttt{r}_1$), the addition of nutrients ($\texttt{a}_1$) can help to remove the excessive quantity of rbCOD, hence prevent filamentous bulking ($\texttt{g}_1$); however, this may lead to an increase of nitrogen and the possibility to encourage nitrification/denitrification ($\texttt{s}_3$), provoking rising sludge ($\texttt{g}_5$).

In this fashion all possible lines of reasoning *w.r.t* the organic matter type discharge and its consequences could be effectively studied, at least questioned.

Once the argument graph is constructed the MA has to determined which the *winning* arguments are. In this example (see Figure 7.6) the following can be considered: there is no evidence posed by any of the participant agents, that the stated *rbCOD* load is safe *w.r.t* to the WWTP current characteristics, thus the line on the left (**Arg3**) is discarded (see Figure 7.7 for a graphical explanation of the mutual attack relations). Therefore, the conflict between **Arg2** and **Arg5** needs to be solved, that is, whether the proposed action (a_2) will correct the problem (s_2). A similar procedure should be started to resolve the conflict between **Arg4** and **Arg6**. On the basis of the domain consented knowledge (articulate in terms of R, A, S and G) and the reputation of the agents involved, different strengths can be given to each of the arguments in order to finally decide which is the *winner* and which course of action is the safest for the actual WWTP performance.

Accordingly, an expert operator of the WWTP (WTA_O) holds with **Arg5** since it *reports* the suitability of changing the WAS control to a proper set point. However, as depicted in Figure 7.5, which is obtained from the general acquaintance model (see Figure 5.7), in critically safety decisions WTA_M has higher reputation and their arguments are ranked better than WTA_O's ones. So the reasoning line containing **Arg4** is preferable.

For this specific case, and without considering past experiences, the discharge is considered safe only if the corrective action of adding nutrients (a_1) does not provoke

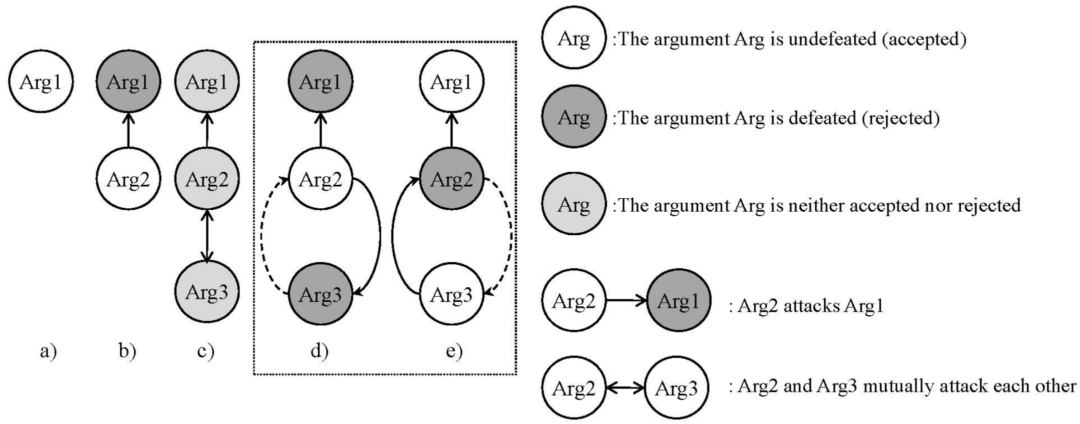


Figure 7.7: Graph of interacting arguments. Detail of one reasoning line possibilities *w.r.t* Figure 7.6. Within the square the two possible final solutions if this reasoning line is authorized.

any secondary effect. In other words, if **Arg6** is accepted as valid, then it attacks **Arg4** and consequently supports **Arg2**. Otherwise, if **Arg6** is false, **Arg4** attacks **Arg2**, so the winning argument will be **Arg1** that claims the safety of the discharge. The several possibilities of attacking/supporting relations in this dialogue example are graphically shown in Figure 7.8. Figure 7.8-d and 7.8-e depict specifically the final decision, *i.e.* the situation hereby presented: depending on the defeasibility of **Arg6**, the action of discharging (a_0) will or will not be supported.

7.2.3 Nutrients example

Some industrial discharges can contribute with nitrates and enhance nitrification within the aerobic reactor and therefore denitrification in the secondary settler overcoming rising sludge (91).

Accordingly, there is an industrial wastewater discharge received by a WWTP. The wastewater contain nitrates, thus WTA believes that the presence of nitrates can enhance rising sludge.

The known facts are:

- there is an industrial wastewater discharge `ind_ww`
- `wwtp` is the receiver of the discharge
- the discharge has *nitrates* content

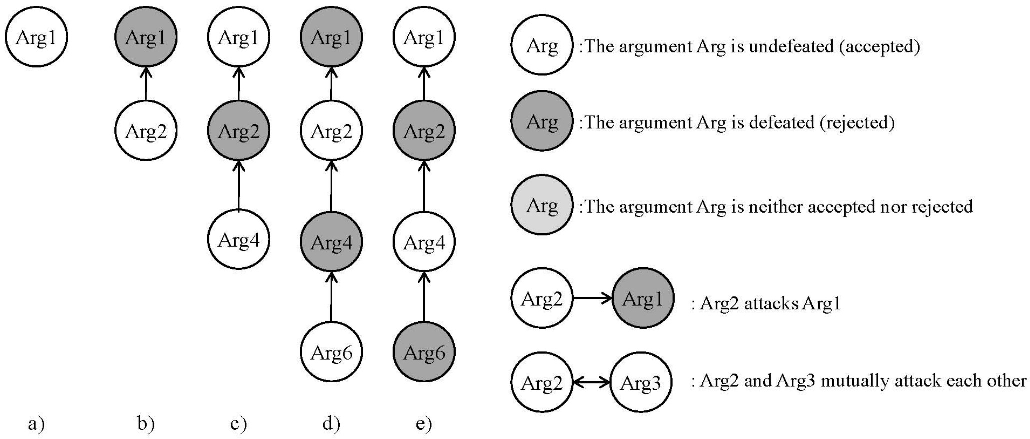


Figure 7.8: Graph of interacting arguments. According to the organic matter example, **Arg1** is an argument in favor of an industrial discharge; **Arg2** attacks **Arg1** arguing the discharge contains a high *rbCOD* load that will cause *filamentous bulking* at the WWTP. **Arg4** defends **Arg1** arguing that there is the possibility to apply a corrective action. However, the application of this action could end with a successful situation or not (*d* and *e*, respectively)

- the current state of the plant is known (by the WTA) thanks the availability of a supervisory system (*i.e.* ATL)
- the process of Denitrification (DN) takes place in the secondary settler with previous Nitrification (NN) in the reactor
- apart of nitrates the following conditions must be also present: (1) a source of organic mater or residual BOD_5 (typically > 10 mg/l); (2) low concentration of DO within the secondary settler (< 0.5 mg/l); (3) Presence of denitrifying bacteria which use nitrate or nitrite ions to degrade soluble BOD present in clarifiers
- solutions are basically a set of actions

The conflict is:

- IA: the discharge can be done safety
  JUSTIFICATION: it complies with legislation.
- WTA: the presence of nitrates is a contraindication.
  JUSTIFICATION: nitrates, together with together with other conditions can cause DN, hence rising sludge.

- WTA_O: a set of actions exists to prevent or mitigate DN in secondary settlers.
  JUSTIFICATION: favor denitrification in reactors by adjusting DO, optimizing SRT and providing adequate anoxic conditions can prevent rising.
  JUSTIFICATION: avoiding DN in clarifiers by increasing WAS to decrease SRT, increasing aeration specially at the last compartments of the reactor can prevent rising.
  JUSTIFICATION: avoiding NN in reactor by increasing WAS or decreasing RAS, decreasing DO and optimizing SRT can prevent rising.

Let us suppose that an industry, represented by its IA, propose the abovementioned wastewater discharge claiming that after it no undesirable effects will occur. Accordingly, IA poses argument $Arg1$:

> **Arg1**: In the current circumstances (*i.e.* a wastewater discharge and a WWTP) industry $\texttt{Ind}_i$ will effectuate the discharge (action $\texttt{a}_0$) claiming that this action ($\texttt{a}_0$) will not cause any side effect S so any undesirable goal G^- to the treatment system.

Following the protocol game presented in Figure 7.3 and answering the critical question *AS1_CQ1: is there a contraindication for undertaking the proposed action?*, the following argument can be submitted:

> **Arg2**: If in current circumstances industry $\texttt{Ind}_i$ effectuate the discharge ($\texttt{a}_0$) containing a high concentration of nitrogen ($\texttt{r}_3$), this will increase denitrification (DN) within the secondary settler instead of within the reactor ($\texttt{s}_3$) and hence provoke the appearance of rising sludge ($\texttt{g}_5$).

Following the same approach as in §7.2.1 and §7.2.2, different experts on the domain can start a dialogue to attack or support Arg2, which poses new important information about the discharge (*i.e.* the discharge contains an excessive quantity of nitrogen that can cause DN and hence, rising).

It is documented that the degree of DN process at the secondary settler depends on a set of conditions such as, apart from the presence of a high concentration of nitrates, a low concentration of DO and the presence of denitrifying bacteria. Denitrifying bacteria use nitrate or nitrite ions to degrade soluble organic matter present in clarifiers. Normally, at warmer temperatures the rate of degradation is higher since the activity of microorganisms increases. However DO concentration will also deplete more quickly in the settled sludge and, consequently, poses a greater potential for DN (91). Three main possible alternative set of actions to prevent this situation are known, which consists on:

- favor nitrification in reactors (a_4),
- avoid denitrification in clarifiers (a_5) and
- avoid nitrification within the reactor (a_6).

According to this, three possible counterarguments exist risen by the critical question **AS2_CQ3**: *Is there a course of action that prevents the achievement of the stated effect?*, which are:

> **Arg3**: If in current circumstances industry $\texttt{Ind}_i$ effectuate the discharge ($\texttt{a}_0$) containing a high concentration of nitrogen ($\texttt{r}_3$), this will not increase denitrification (DN) within the secondary settler ($\texttt{s}_3$) since a set of actions to favor denitrification in reactors (a_4) will prevent the appearance of rising sludge ($\texttt{g}_5$).

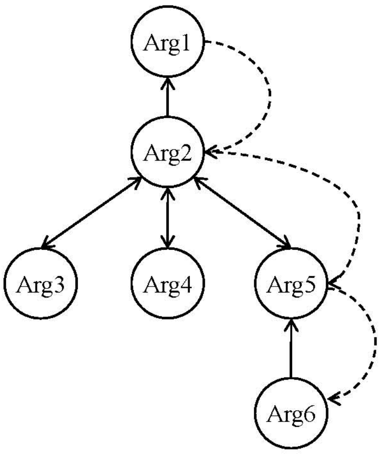
> **Arg4**: If in current circumstances industry $\texttt{Ind}_i$ effectuate the discharge ($\texttt{a}_0$) containing a high concentration of nitrogen ($\texttt{r}_3$), this will not increase denitrification (DN) within the secondary settler ($\texttt{s}_3$) since a set of actions to avoid denitrification in clarifiers ($\texttt{a}_5$) will prevent the appearance of rising sludge ($\texttt{g}_5$).

> **Arg5**: If in current circumstances industry $\texttt{Ind}_i$ effectuate the discharge ($\texttt{a}_0$) containing a high concentration of nitrogen ($\texttt{r}_3$), this will not increase denitrification (DN) within the secondary settler ($\texttt{s}_3$) since a set of actions to avoid nitrification in reactor ($\texttt{a}_6$) will prevent the appearance of rising sludge ($\texttt{g}_5$).

As mentioned before, Arg3, Arg4 and Arg5 introduce alternative/preventive actions. These may in turn warrant or cause some undesirable secondary effect(s) (AS3,4,5_CQ1). Accordingly one possible new argument can be posed by an expert on the domain:

> **Arg6**: If in current circumstances industry $\texttt{Ind}_i$ effectuate the discharge ($\texttt{a}_0$) containing a high concentration of nitrogen ($\texttt{r}_3$), the enhancement of nitrification in the reactor ($\texttt{a}_6$) can provoke DO depletion ($\texttt{s}_4$), hence overgrowth of some *filamentous bacteria* ($\texttt{s}_2$) causing filamentous bulking ($\texttt{g}_1$).

The case of nitrification/denitrification enhanced by an excessive load of nutrients at WWTP's input is complex. Other possible lines of reasoning should be considered to effectively study the problem. However, as the problem of nutrients at WWTPs is not the aim of this work, hereby only the most relevant are depicted.



ID	Argument	Proponent Agent
Arg1	<R(ww, wwtp), A(a_0), S( ), G^-(nil)>	IA
Arg2	<R(ww(**r_3**), wwtp, A(a_0), S(**s_3**), G^-(**g_2**)>	WTA
Arg3	<R(ww(r_3), wwtp), A($a_0 \cup$ **a_4**), S( ), G^-(nil)>	WTA_O
Arg4	<R(ww(r_3), wwtp), A($a_0 \cup$ **a_5**), S( ), G^-(nil)>	WTAo
Arg5	<R(ww(r_3), wwtp), A($a_0 \cup$ **a_6**), S( ), G^-(nil)>	WTA_O
Arg6	<R(ww(r_3), wwtp), A(a_0 , a_6), S(**s_4** $\cup$ **s_2**), G^-(**g_1**)>	WTA_M

Attack relation	⟶
Dialogue move	- - - - - ->

Figure 7.9: Graph of interacting arguments of the nutrients (nitrates) example.

Once the argument graph is constructed (see Figure 7.9) the MA has to determine which the *winning* arguments are. In this specific example the higher reputation of WTA_M posing **Arg6** defeats **Arg5**, so defeats the support of the alternative action of avoiding nitrification within the reactor (a_6) since it can provoke problematic secondary effects. Therefore, the conflict between **Arg2** and **Arg3** needs to be resolved. That is, whether the action of favouring the nitrification in reactors is enough to prevent the problem. An analogous procedure should be started between **Arg2** and **Arg4**. Graphically, the case of *mutual attack* between arguments was depicted in Figure 7.7. Following the same procedure the mutual attack between Arg2 $\leftrightarrow$ Arg3 and Arg2 $\leftrightarrow$ Arg4 can be resolved. Let us suppose that the authorized reasoning line of nutrient's example graph (see Figure 7.9) is the one on the left. That is, WTA_O claims that the action a_4 of settling the conditions to favour nitrification in reactors will prevent the problem of rising. Given this situation, **Arg3** defeats **Arg2** and hence **Arg1** is supported. In conclusion, the discharge could be done, obviously taking into account all these considerations.

7.3 Conclusions

The principal conclusions of this chapter can be listed as follows:

- The *ProCLAIM* model has been used with the aim to allow the agents (of the proposed MAS in Chapter 5) to participate in a deliberated decision-making process to finally take the safest environmental decision.
- The success of the deliberation can be, up to some extent, biassed by the participants argumentation ability rather that on their knowledge of the problem at hand. To overcome this problem, *ProCLAIM* has a lower layer of abstraction containing the specialized AS proposed by Atkinson in (16).
- These more specific AS, not only are tailored for arguing over an action's safety but they are specialized for the deliberation in a particular scenario. They are aimed to capture the scenario's stereotypical reasoning patterns. Examples of scenario specific schemes were given in §7.2.1–§7.2.3.
- Accordingly, *ProCLAIM* model (that was formalized by Tolchinsky *et al.* in (194; 195)) permits to carry out Atkinson's dialogue game by:
  - referencing knowledge sources that are instantiated by means of AS and CQ.
  - referencing previous dialogues (cases)
  - referencing the agents' reputation

To sum up, we have proposed the use of a dialogue game for deliberating over action proposals in urban wastewater system contexts, providing:

- the basis for the construction of the specialized ASR,
- the formalization and application of the protocol-base exchange of arguments within the overall *ProCLAIM* framework for a specific domain.

Chapter 8

Discussion

The advantages and limitations of the methodological approach (Chapter 3 and 4), the development of the model (Chapter 5) and some scenario implementations (Chapter 6 and 7) are discussed. The discussion will be structured with the aim to visualize some important connections between the several chapters of this document, and to discuss the suitability and appropriateness of the agent-based approach proposed along the thesis document. Although the model and the scenario implementations are the visible results of this process, the process itself is the most important part. Finally, we write some synergies found between the used approaches.

8.1 Problem analysis and possible solution

The increase of several processes, such as urbanization and industrialization, has lead to a high consumption of natural resources and consequently, negative effects on the sustainability of the environmental quality have risen. At the river basin scale, urban catchments are of special concern, since they are composed by several elements which are sources of wastewater pollution that can damage the final receiving media.

The description of the main components, interrelations and relevant regulations of the environmental system under study has permitted us to point out the most recurrent and important problems. The majority of these environmental problems at all scales – from the merely local to those with long-term global significance – raise certain fundamental issues which make their resolution difficult and controversial. Some recurrent issues, many of them interrelated, include the following (19; 157; 167):

- Environmental problems are *multidisciplinary* by nature. As a consequence, in most environmental management situations, a single expert who can solve the problem entirely does not exist. Different opinions about the causes, consequences and possible solutions for the problem exist. Thus, conflict is inherent when trying to solve environmental problems due to the multiplicity of views and interests involved.

- Environmental problems are often characterized by great *uncertainty*. The complexity of environmental systems means that our understanding of the human impact upon it is very partial, and accurate prediction is often impossible. Collected environmental information is often imprecise, uncertain or erroneous. As knowledge advances, uncertainties are reduced, but they can rarely be eliminated.

- Environmental problems involve strong *spatial* and *temporal distribution*. The multiplicity of scales has been traditionally associated with distinct spatial scales (*i.e.* local, regional, global), each associated with specific timescales. The irregular distribution of environmental problems in time and space make difficult to well define the interactions among these scales.

- Environmental problems are hard to model and understand. Environmental problems, as well as environmental systems, are *dynamic* in nature, and therefore deep models of their behaviour are difficult to reproduce.

The experts' reasoning about environmental problems and decision making about suitable solutions is understood, in environmental contexts, as manipulating high amount of specific data, mathematical models of the real situation, simulations, *etc.* In case of *inaccessibility*, *incompleteness*, or *incorrectness* of data as well as in other situations with high degree of uncertainty, experts still are able to make decisions. However they need to understand, in a limited time, chemical, physical and biological processes in relation to socioeconomic conditions and applicable legislative framework. The high complexity of environmental problems, characterized by the aforementioned most frequent issues, has lead to the use of knowledge-based decision support tools in decision processes.

Agent-based approaches have introduced both a powerful metaphor and a group of technologies in the field of IEDSS, giving support to the management of environmental problems, mainly of those concerning the management of renewable resources (*e.g.* water management, biodiversity management, forest management, erosion and soil management, *etc.*). These problems represent typical dynamic and unpredictable multi-agent domains, where flexible autonomous action is required to adapt to changing conditions. The need to cope with dynamic and emergent situations requires application components to interact in more flexible ways. The characterization in terms of *agents* has proven to be a most natural abstraction to many real world problems, having convinced researchers and developers in a wide variety of domains *e.g.* (12; 99; 140) of the great potential of multi-agent solutions.

Briefly, for *modular*, *decentralized*, *changeable*, *ill-structured* and *complex system*, such as the system described hereby, software intelligent agents are really appropriate (148).

8.2 Methodological framework

The *state of the art* in agent-based approaches applied to environmental issues shows the utility of agents as solvers of environmental problems. The applications and agents used are heterogeneous in nature: although most of them refer to natural resources management (*i.e.* from water sources, air or soil), other environmental issues are also faced using agents. Their coupled work permit to go beyond their individual capabilities or knowledge. All these applications have some of the general characteristics of MAS reported in (186):

- each agent has incomplete information or capabilities for solving the problem. Thus, the importance of MAS is concerned with the behaviour of a collection of agents designed at solving a given problem together;
- there is no global system control;
- data is decentralized, and
- computation is asynchronous.

The design of the systems studied is mainly done using agent-based concepts whereas for their implementation the use of object-oriented technologies prevails. The systems are partially validated: in most of the cases the model used to describe the agents is validated through expert knowledge, whereas the overall system performance validation is a further step that requires more work and research to be done.

As concluded by Athanasiadis in (12), agent-based technology is not homogeneously adopted in environmental software developments. However, an increase in the use of agent platforms to develop the systems is observed. Even though the fuzzy classification of the systems into the three groups described in §3.1 (*i.e.* EDMS, EDSS, ESS), no interrelation between the type of agent-based environmental system and the technology used can be observed.

Design and implementation of MAS aimed at solving environmental problems require research in order to tackle with many challenges. Some of the most important and tricky ones were listed in (99), and are still important questions by researchers in the field of MAS applications. Answers to these questions are naturally interrelated. Some answers are found within the reviewed systems presented in this *state of the art* and some others, for some specific environmental problems, were published, together with Chapter 3, in (58).

8.3 Solution design

In Chapter 5 we have applied the agent-based features to design and conceptualize the UWS. A reduced scale model of a municipal wastewater system has been described by means of agents, with the purpose to serve as the template behaviours for building any size municipal wastewater system using real time equipment.

UWS activities involve multiple organizations at various administrative levels, each one having their own systems, services and interests. In many cases, the capacity (and will) to share relevant information between organizations is limited. In the best of the cases is forced by law. This limits the chances of preventing the impact of human activities in the river. The use of agents is meant to challenge the problems related with information sharing and to improve the interoperability among actors in order to support better coordination and more informed decision-making.

The results of applying the agent-oriented design for the UWS are three different but interrelated models: the agent model, the service model and the acquaintance model for the wastewater scenario. Such design, in terms of agents, adds several useful aspects to the modelling tasks *w.r.t* having simply objects or elements. Some of the advantages encountered while conceptualizing the UWS using an agent-based oriented design are the following:

1. It provides a way to better integrate data and information from heterogeneous sources and to better distribute the data.
2. It provides the possibility to establish a more direct and natural communication and coordination between the elements and the possibility to keep the history of the course of the interaction between them. However, although communication between the agents can multiply their effectiveness (131; 214), for each specific

implementation it should be evaluated to what extent and for what tasks inter-agent communication significantly improve the desirable performance in comparison with other local methods for conflict resolution.

3. It provides a major abstraction and consequently a higher adaptability to the environment and to changing conditions, thanks to the capacity of MAS to accept new elements (*i.e.* new industries entering the system could be easily modelled according the abstractions provided here for industry agent and roles).

4. Moreover, the possibility to coordinate their actions by working in a cooperative fashion adds a greater value than the one that can be obtained from any individual or even integrated mechanistic model. For instance, in the urban wastewater domain, some activities need to be coordinated because of shared resources (*i.e.* the WWTP), or because some activities depends upon others activities (*i.e.* industrial discharges require a permission from water authorities) or just because, intuitively, working proactively agents self-utility increase.

With this solution it is shown that agent-methodologies are a useful tool to analyze the system and better explain how it should work. Also, are important to raise awareness of the advantages and problems of open systems. The development of agents, independently of their complexity, help to more accurately describe the activities and processes occurring into the system. In special, those related with: accessibility to information, interoperability and coordination.

8.4 Development: prototyping knowledge inference and dialogues

In the first chapters of this thesis (Chapters 3 and 4) we depicted the main concepts of an agent-based approach, focusing on the analysis and design of the model. Here we discuss the development phase in which we propose a proper specification of the domain particular knowledge.

Along this thesis document we have depicted *why special tools to specify the domain knowledge are required.* In particular, industrial wastewater discharges represent a main concern for WWTP managers. The variability of possible industrial discharges, the complex and often uncertain knowledge and information related to the activated sludge based processes to treat wastewater, make the management of industrial discharges both a challenge and a problem. It is of special importance the use of timely and precise information to understand and make decisions about the stated problem, as well as, to develop criteria for evaluating the possible solutions for each situation. Knowledge-driven approaches are gaining strength thanks to their relevance and usefulness in the area of environmental modelling and environmental decision-making processes.

The proposed case study was aimed to properly assess the contribution from industries in order to avoid the transfer of polluting substances in the effluent and consequently to the river. However, the same knowledge-based approach can be appropriate to model other temporal or spatial heterogeneities of the river basin system.

Two complementary, and in some aspects overlaid, approaches were presented:

1. In one hand, and from the more formal argumentation point of view, we used a possibilistic-based argumentation approach (Chapter 6). The approach offers some natural mechanisms for dealing with reasoning under inconsistent information. Specifically, for domains where inconsistent knowledge bases are common, such as the river basin scenario presented, we have shown that it is useful to consider inconsistencies. For instance, by considering them, we keep important information (*e.g.* the doubt of having or not a problem at the WWTP, or at the river), which at the end will allow to make better informed decisions. Specifically, in this approach, we saw that:

- Finite state automata are useful to represent cause-effect relationships, essential in order to assess decisions in this domain.
- The proposed hierarchical structure permits to frame the degree of uncertainty related to the domain knowledge.
- The codification of this knowledge in terms of a possibilistic declarative language permits to:
  - Ddirectly execute the codified programs (so the overall complex diagnosis process is automated),
  - specify the cause-effect relations,
  - represent uncertainty degrees related to expert opinions, and
  - perform a non monotonic approach reasoning.

2. On the other hand, and from a more practical argumentation point of view, in Chapter 7 we proposed to address the question of *how* to support decision making, as an argumentative process, in which the knowledge available in the decision trees can be equally accounted for and represented as interacting arguments. The added value of this approach is that, in the argumentative process, alternative proposals or the identification of a potential complication caused by the interaction among diverse factors can naturally be integrated into the decision making *via* the submission of arguments and counter-arguments. In particular, this approach facilitates the active participation of different experts in the decision making and to aggregate their contributions. Specifically, the presented tool:

- focuses on the negative side effects of a given problem instead of focusing on positive ones, in order to prevent or mitigate them. This makes less difficult to explore the current context and possible actions, and thus articulates the problem beyond numerical thresholds;
- proposes a different way to conceptualize the decision making process in order to offer a reliable source of understanding the problems, jointly with possible solutions (*e.g.* alternative actions). This new conceptualization allows to proceed beside legislation while also taking into account the actual state of the WWTP facilities and other relevant factors in order to make a fully informed decision;
- the introduced circuite of schemes linked *via* their associated CQ define a protocol-based exchange of arguments are specialized for deliberating over whether a proposed action will or will not cause an undesirable side-effect in the environment.

As we pointed at the beginning of the discussion, these approaches are complementary but some aspects are overlaid. Accordingly, we should like to discuss some observed synergies between the two approaches:

- The process of critical questioning could result useful to build more accurate automata. That is, to decide the parameters that define states of automata could be retrofitted by this natural, and now well bounded, process of critical questioning.
- The formalization used in Chapter 7 by means of a 5-tuple could be directly parcelled to the ASP specification. In this way, the information coming from the natural process of argumentation by using AS and CQ, could be entered in the formal proposed possibilistic-argumentation-framework presented in Chapter 6.
- The process of giving an uncertain value to the arguments could be retrofitted by *ProCLAIM* model with some of its knowledge sources parts. More concretely,

recovering past dialogues (cases) and using the reputation of agents could add more reliability to the value of the uncertainty labels.

However, further work needs to be done in order to achieve a better approximation to the real domain. Some points on this aspect will be discussed in §9.2.

Figure 8.1 intends to depict the interactions of all these approaches *w.r.t* the studied domain. At the bottom of the figure we draw some important factors that depict the complexity of wastewater management in river basins. At the bottom of the figure, a simplification of the agent-based conceptualization is depicted. In between, the dashed square outstand the issues we have dealt with in this thesis document.

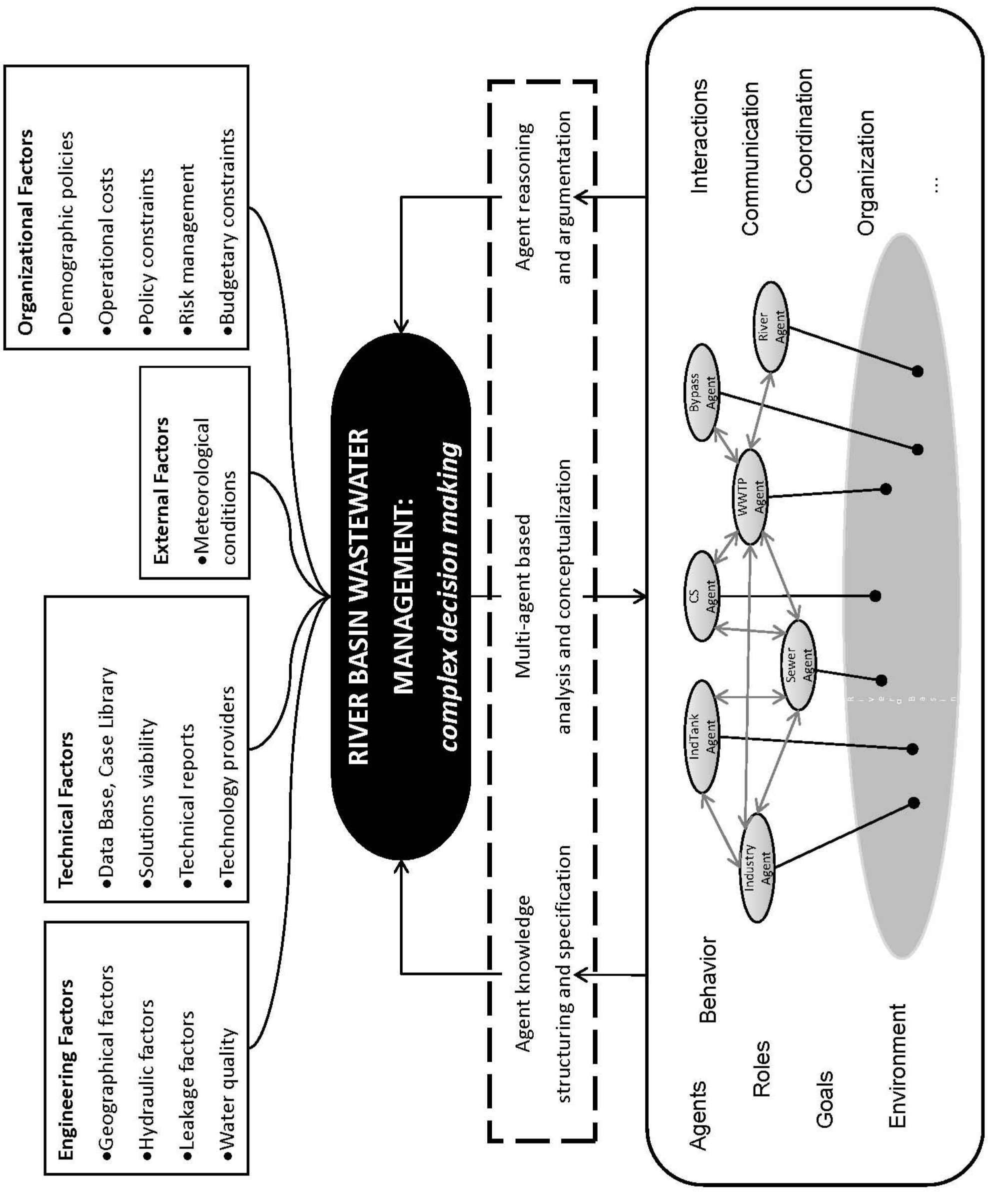


Figure 8.1: Multi-agent based approach to deal with wastewater management in a river basin context

Chapter 9

Conclusions

The goal of this research project was to build a knowledge-based model enabling agents' argumentation to improve the management of industrial discharges in a river basin, augmenting the reliability of environmental decisions in this context. This implied the acquisition of a deeper understanding of the interactions and dynamics between the several components of the system. This involved as well to find appropriate ways to represent and specify this interactions and the complex knowledge involved.

9.1 Conclusions

To meet the principal thesis goal, the following research objectives were pursued and achieved:

1. The **review** on agent-based modelling applications in the field of environmental management permits us to conclude the appropriateness of agent-based methodologies to be used to manage environmental complex systems. The several agent-based applications differ on their purpose, their software design and development. But, they have in common the capacity to capture the behavioural complexity of reality. Unfortunately, the implementation and evaluation degree is not habitually performed or achieved yet.

2. The **study** of the main concepts in two directions *i.e.* in one side on IRBM and IUWS management, and on the other side, on agent-based modelling and reasoning, permit us to frame the **problem** under study. Concretely, the most relevant conclusions derived from this study are:

    - Industrial wastewater discharges are an important source of pollution in

UWS for both the quantity and quality variability of discharges. Wastewater pollution management in river basins is a problem that keep all the challenges related to environmental management problems *i.e.* it is multidisciplinary, it is distributed in space and time, it is dynamic and entails a lot of uncertainties due to the features of ecological systems. Accordingly, better measure tools are needed to acquire more and more accurate information. This will allow to enhance reasoning to better support decision-making processes.

- Information related to environmental systems is characterized lots of times by its inaccessibility, incompleteness and even incorrectness. In this area more knowledge is needed to assess the safety of polluting substances once in the environment. Many feedbacks, side effects, *etc.* are still not known.
- There is legislation with the aim to prevent pollution, but it is not always applied effectively; fixing thresholds is not a simple task and, to confront the variability of the system, static thresholds are not always appropriate.
- The shared responsibility and the coordination of all involved stakeholders is crucial to manage wastewater pollution. Assessment founded on knowledge-based approaches and distributed among several agents emerges as an appropriate tool. Agent-based tools are specially designed to address temporally and spatially distributed problems, such as those related to wastewater pollution management.

3. The **multi-agent based** modelling approach has permitted us to **model** the UWS, and to find reusable patterns of behaviour of the agents in the system. The three principal components of the model are:

    - The agent model, containing the agents and their internal structure. Ten agents and ten roles have been described in the approximation presented in this thesis. This is a primary but novel approach that set off the way to model new agents and behaviours in the system studied.
    - The interaction model, containing the detailed definition of the interaction protocols and the content of the exchanged information.
    - The organizational model, containing an overview of the connections among agents.

4. The use of **argumentation** techniques, according to two of its major achievements, that is:

- to elicit and infer relevant (new) knowledge *w.r.t* the domain under study; to evaluate and deliberate possible conclusions (*e.g.* diagnoses, actions, plans, *etc.*), even if they result to be inconsistent;
- to permit the experts participation in argumentation-based decision making and argumentation-based dialogues,

has permitted us a new way to conceptualize the decision making process in our domain. It offers a reliable source of understanding the problems, jointly with possible solutions (*e.g.* alternative actions, plans of actions, *etc.*). This new conceptualization allows to proceed beside legislation while also taking into account the actual state of the WWTP facilities and other relevant factors in order to make a fully informed decision. Accordingly, the use of an agent-argumentation based component as DSS proposed in the main thesis has been achieved.

5. The use of **ASP** is an appropriate formalism to represent and capture the characteristics of the domain. By using ASP we have encoded information as logical rules, and solutions are obtained as sets of models. Each model is a minimal set of atoms representing information and deductions obtained by applying some rules. So, conclusions rely on present and unavailable information, they form a coherent set of hypotheses and represent a rational view on the world described by the rules. As a general observation of this formalism, we obtained not a unique set of conclusions but possibly many ones and each conclusion is no longer absolutely certain but only plausible and more or less certain (since it permits to qualitatively capture the uncertainty).

9.2 Future work

As a result of this work, we envision some promising future lines of research, which will require a lot of interdisciplinary work:

- To construct an *ontology* to manage the knowledge related to industry types, pollutants, polluting potential, *etc.* A clustering and categorization could be done to provide the basis knowledge to build the declarative rules and hence the arguments.

- To use an editor to build the arguments, in order to have a better storage of them and to make easy the development of the argument scheme repository to be used by *ProCLAIM* .

- To extend the argumentation framework to permit the development of plans of actions automatically (such as achieved with the diagnosis phase).
- To analyze the possibility to integrate the *ProCLAIM* model and the possibilistic-argumentation framework.
- To *full implement* the model by using different utilities. By means of agent-based simulations several aspects of the model could be tested and refined (different agents, roles, tasks, *etc.*). For example, one possible utility could be to forecast the outcome of some pollution-prevention policy strategy. Once a simulation platform would be realized, it could be very interesting to extend the agent-based modelling framework to permit the agents and roles to dynamically change during a run-time simulation. In this direction there is the possibility to establish collaboration with an European Founded Project (6), aimed at developing tools to permit this, among other objectives.
- To perform an *evaluation* phase based on the execution of existing and well-documented cases of discharges that would be used as gold standards. A qualitative evaluation coming from the environmental and wastewater managers would be a good addendum to the work as well. In the long run the evaluation could be performed on a real basin.

Appendix A

Interaction protocols and messages

This appendix contains the interaction protocols and messages exchanged for the agent-based UWS described in Chapter 5.

An Agent Interaction Protocol (AIP) describes a communication pattern as an allowed sequence of messages between agents and the constraints on the content of those messages (141). Patterns are ideas that have been found useful in one practical context and can probably be useful in others. Accordingly, AIP provide us with reusable solutions that can be applied to various kinds of messages sequencing we encounter between agents.

The Foundation for Intelligent Physical Agents (FIPA)[13] was formed in 1996 to produce software standards for heterogeneous and interacting agents and agent-based systems. We have instantiate the appropriate formal standards for our specific scenario. As follows, we have used:

- The FIPA Query Interaction Protocol that allows one agent to request to perform some kind of action on another agent, *e.g.* Query-Discharge-Characteristics (76).
- The FIPA Request Interaction Protocol that allows one agent to request another to perform some action (77), *e.g.* Request-Bypass.

[13]URL: http://www.fipa.org

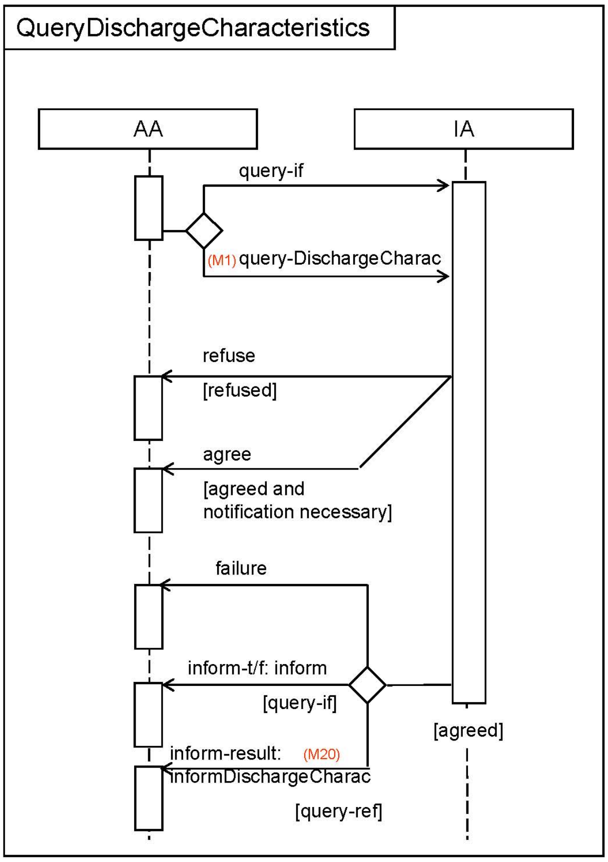


Figure A.1: Query discharge characteristics protocol (AA-IA)

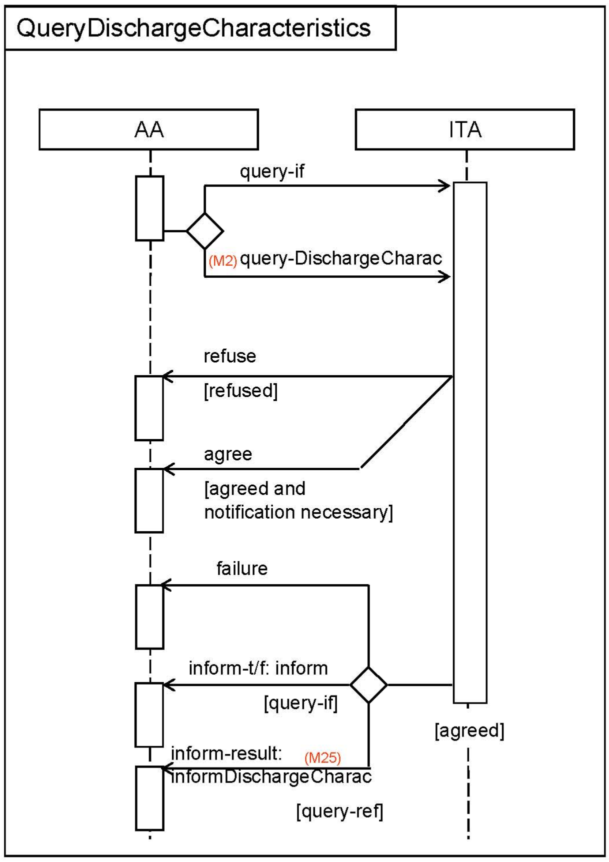


Figure A.2: Query discharge characteristics protocol (AA-ITA)

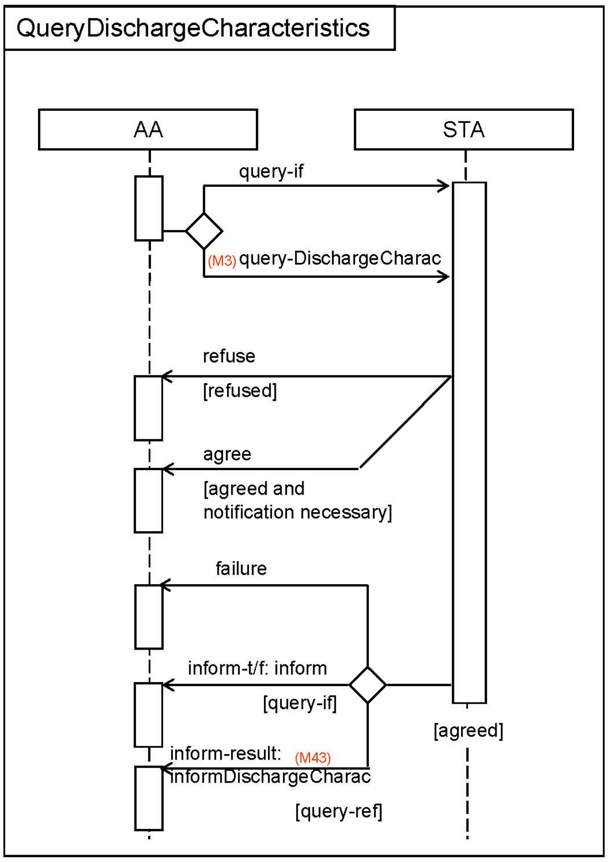


Figure A.3: Query Discharge Characteristics protocol (AA-STA)

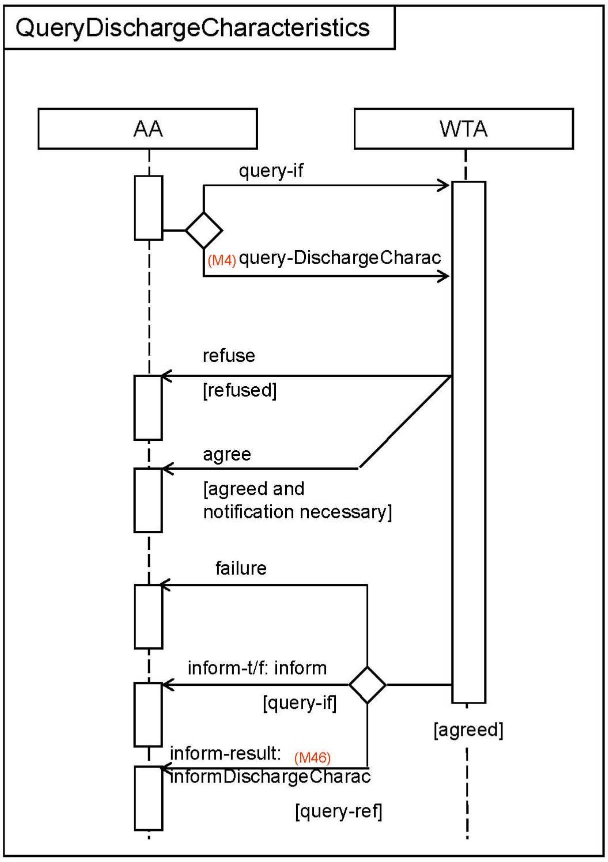


Figure A.4: Query discharge characteristics protocol (AA-WTA)

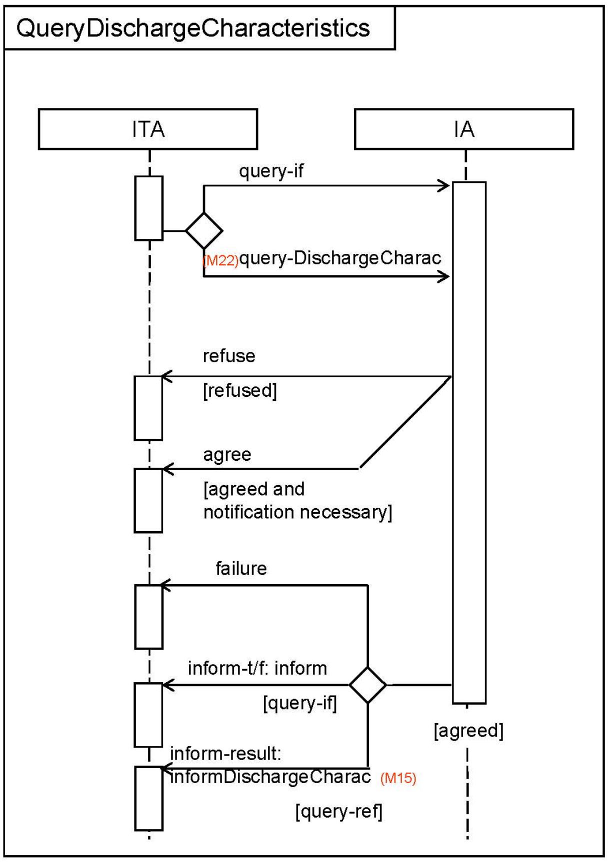


Figure A.5: Query discharge characteristics protocol (ITA-IA)

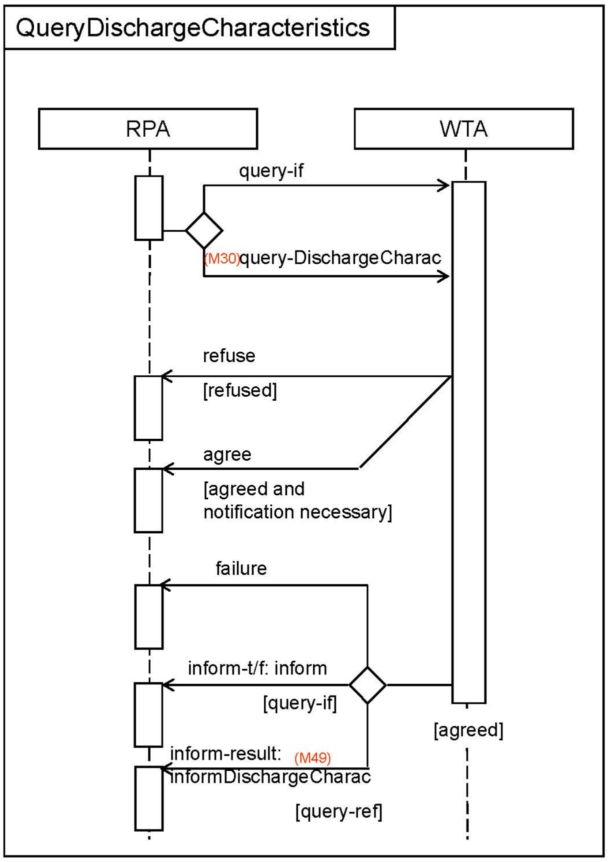


Figure A.6: Query discharge characteristics protocol (RPA-WTA)

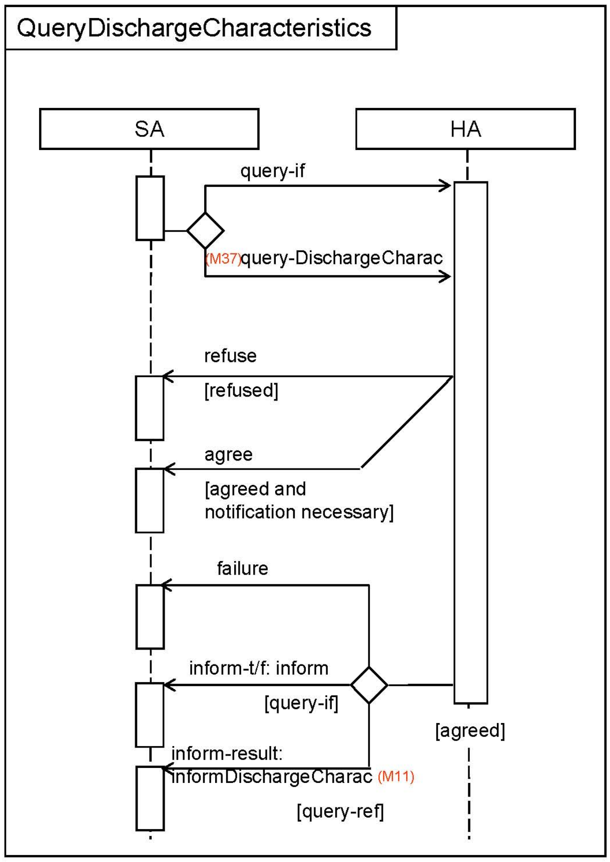


Figure A.7: Query discharge characteristics protocol (SA-HA)

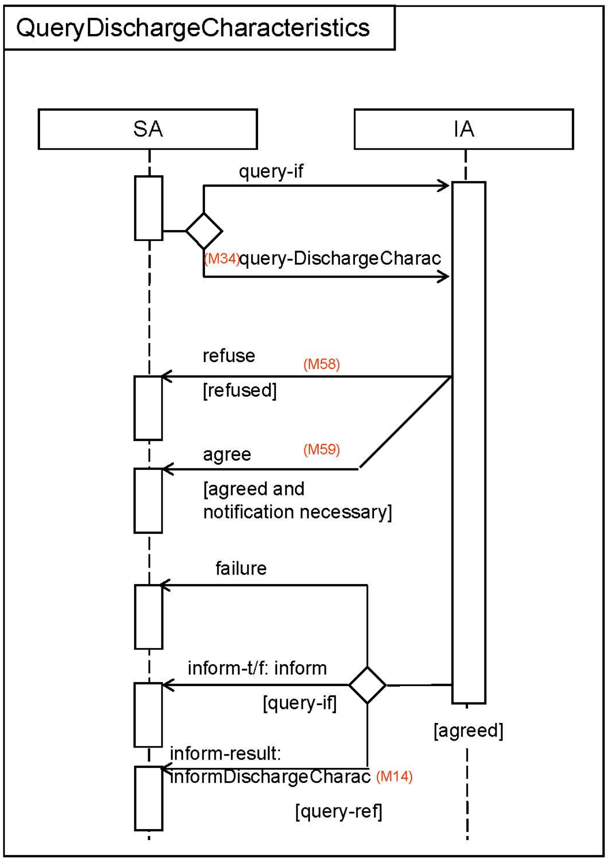


Figure A.8: Query discharge characteristics protocol (SA-IA)

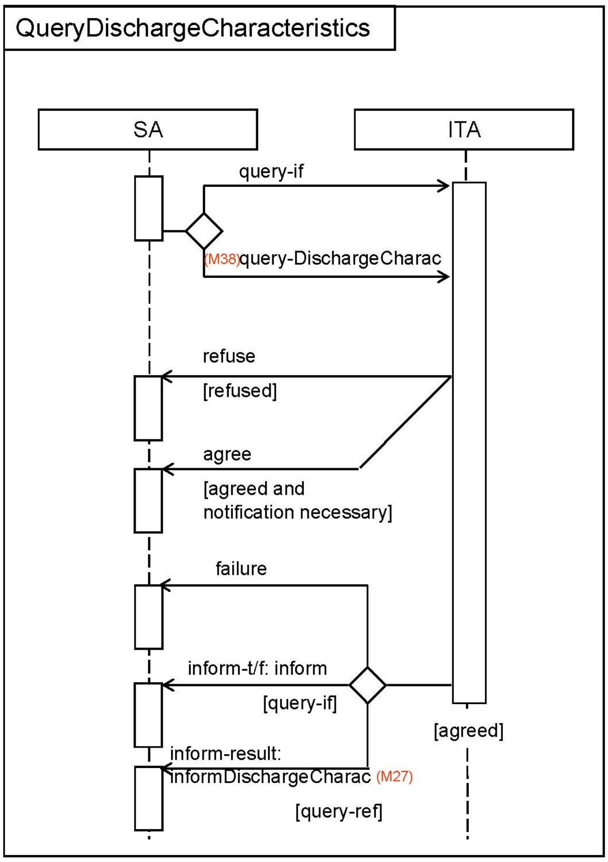


Figure A.9: Query discharge characteristics protocol (SA-ITA)

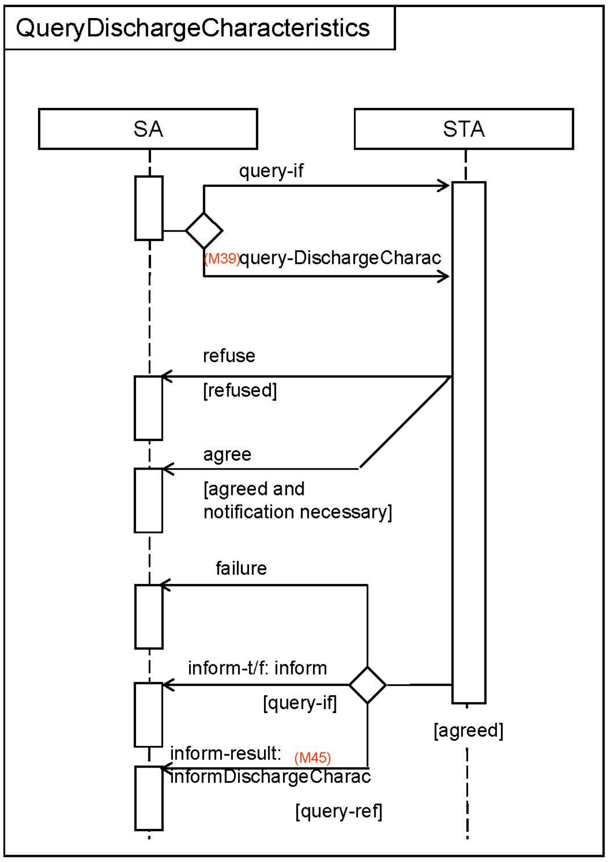


Figure A.10: Query discharge characteristics protocol (SA-STA)

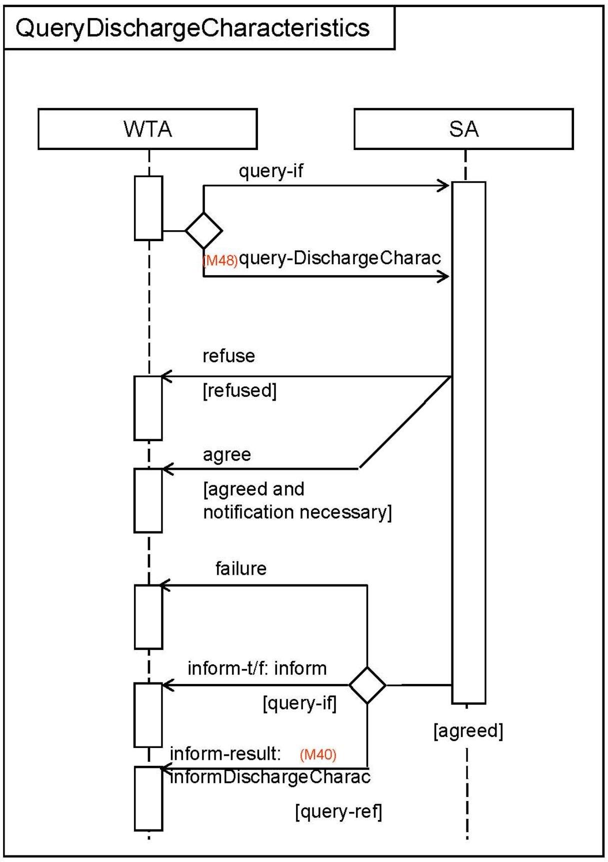


Figure A.11: Query discharge characteristics protocol (WTA-SA)

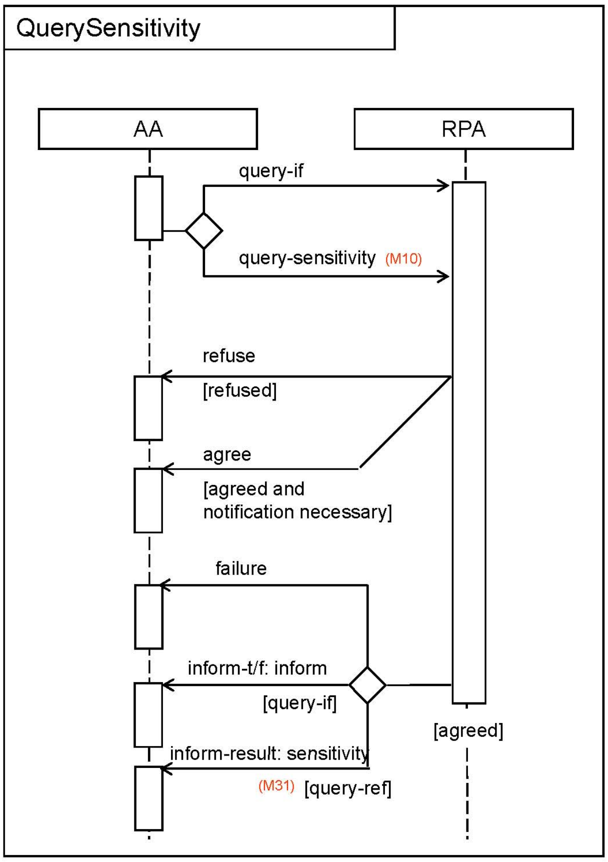


Figure A.12: Query sensitivity protocol (AA-RPA)

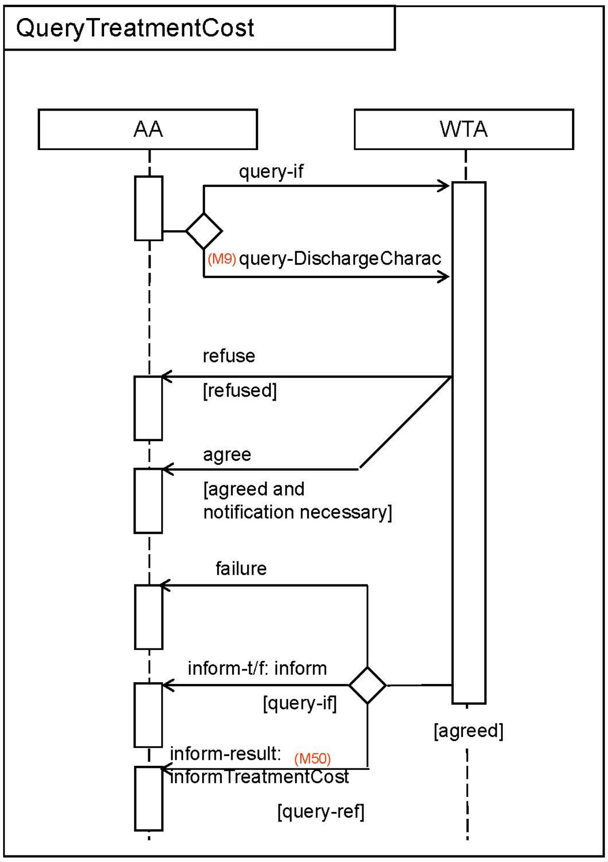


Figure A.13: Query treatment cost protocol (AA-WTA)

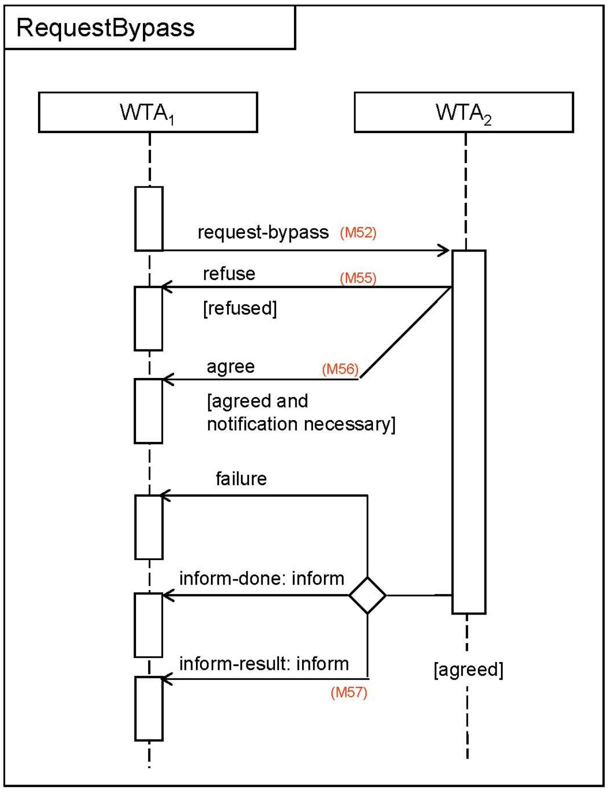


Figure A.14: Request bypass protocol

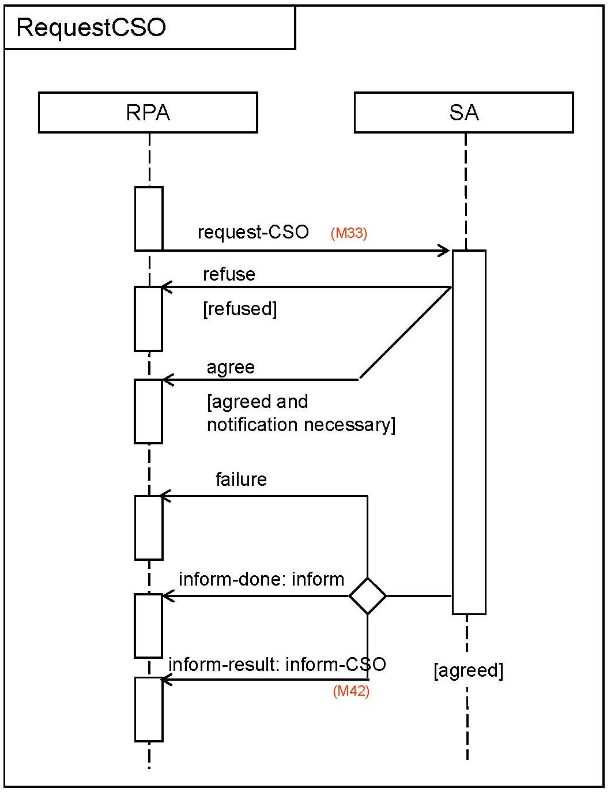


Figure A.15: Request CSO protocol

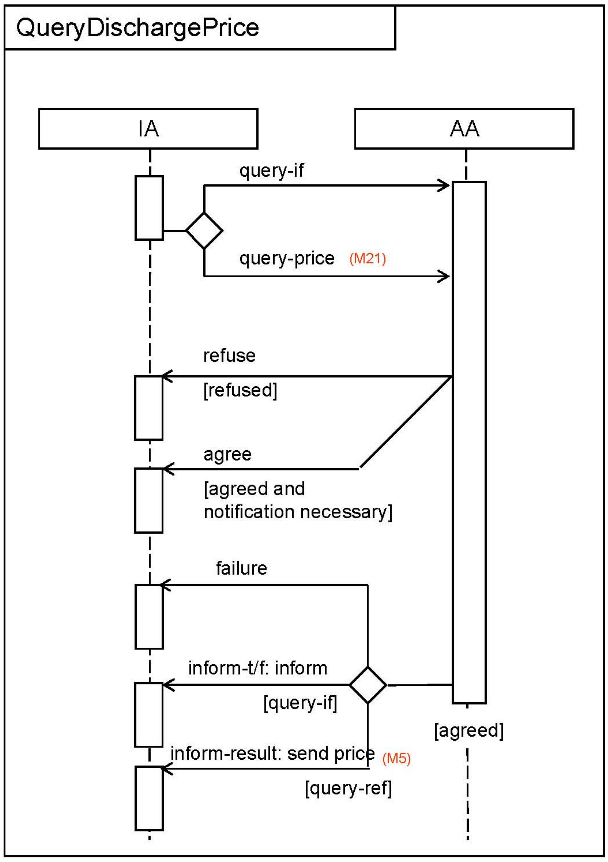


Figure A.16: Request discharge price protocol

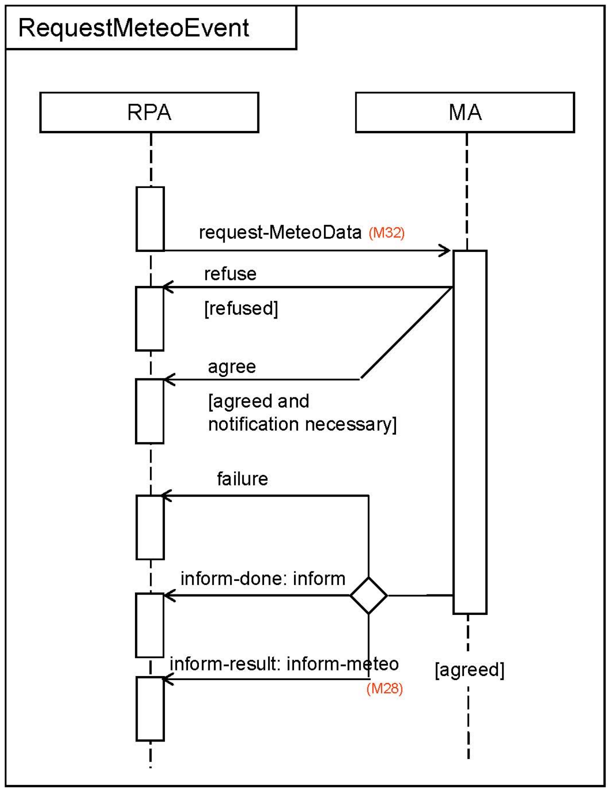


Figure A.17: Request meteorological event protocol

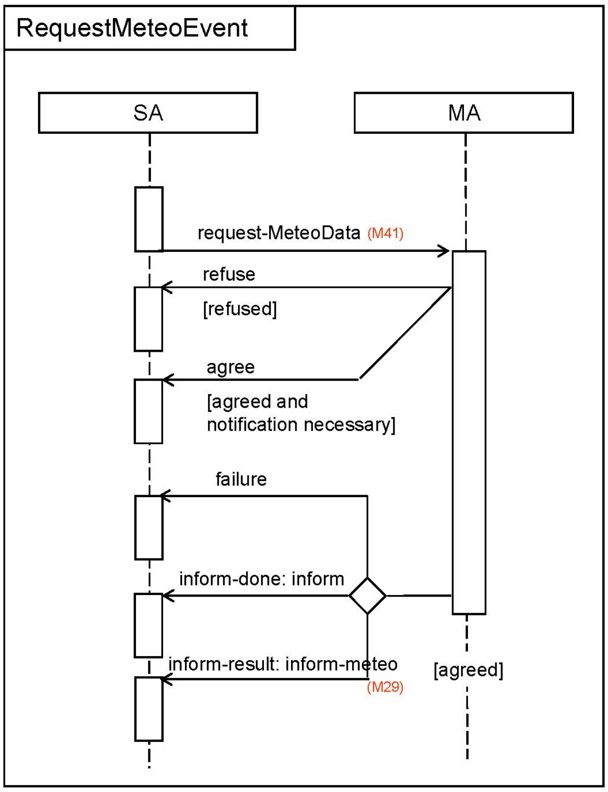


Figure A.18: Request meteorological event protocol

ID	Message	Sender	Receiver	*Performative*	Content	Protocol
M1	QueryIndustryDischarge Characteristics	AA	IA	*query-ref*	<discharge characteristics?>	QueryDischargeCharacteristics
M2	QueryIndTankDischarge Characteristics	AA	ITA	*query-ref*	<discharge characteristics?>	QueryDischargeCharacteristics
M3	QuerySewerTankDischarge Characteristics	AA	STA	*query-ref*	<discharge characteristics?>	QueryDischargeCharacteristics
M4	QueryWWTPDischarge Characteristics	AA	WTA	*query-ref*	<discharge characteristics?>	QueryDischargeCharacteristics
M5	SendPrice	AA	IA	*inform-result*	<price, €>	QueryDischargePrice
M6	SendPrice	AA	ITA	*inform-result*	<price, €>	QueryDischargePrice
M7	SendPrice	AA	STA	*inform-result*	<price, €>	QueryDischargePrice
M8	SendPrice	AA	WTA	*inform-result*	<price, €>	QueryDischargePrice
M9	QueryTreatmentCost	AA	WTA	*query-ref*	<cost of treatment?>	QueryTreatmentCost
M10	QuerySensitivity	AA	RPA	*query-ref*	<type of sensitivity?>	QuerySensitivity
M11	InformDomestic Characteristics	HA	SA	*inform-result*	<HA discharge characteristics>	QueryDischargeCharacteristics
M12	ProposeIndustryDischarge	IA	SA	*propose*	<discharge; cost discharge<cost production> <discharge; receiver point of view?>	ProposeDischarge
M13	ProposeIndustryDischarge	IA	ITA	*propose*	<discharge; cost discharge<cost production> <discharge; receiver point of view?>	ProposeDischarge
M14	InformIndustryDischarge Characteristics	IA	SA	*inform-result*	<COD, BOD, TSS, N, Flow>	QueryDischargeCharacteristics
M15	InformIndustryDischarge Characteristics	IA	ITA	*inform-result*	<COD, BOD, TSS, N, Flow>	QueryDischargeCharacteristics
M16	AgreeDischargeConditions	IA	SA	*agree*	<discharge; conditions established>	ProposeDischarge
M17	AgreeDischargeConditions	IA	ITA	*agree*	<discharge; conditions established>	ProposeDischarge
M18	RefuseDischargeConditions	IA	SA	*refuse*	<no-discharge; why not>	ProposeDischarge
M19	RefuseDischargeConditions	IA	ITA	*refuse*	<no-discharge; why not>	ProposeDischarge
M20	InformIndustryDischarge Characteristics	IA	AA	*inform-result*	<discharge characteristics>	QueryDischargeCharacteristics
M21	QueryDischargePrice	IA	AA	*query-ref*	<price of discharge?>	QueryDischargePrice
M22	QueryIndTankDischarge Characteristics	ITA	IA	*query-ref*	<IA discharge characteristics?>	QueryDischargeCharacteristics
M23	AcceptIndustryDischarge	ITA	IA	*accept*	<yes discharge; conditions of agreement>	ProposeDischarge
M24	RejectIndustryDischarge	ITA	IA	*reject*	<no discharge; conditions of rejection>	ProposeDischarge
M25	InformIndTankDischarge Characteristics	ITA	AA	*inform-result*	<discharge characteristics>	QueryDischargeCharacteristics
M26	QueryDischargePrice	ITA	AA	*query-ref*	<price of discharge?>	QueryDischargePrice
M27	InformIndTankDischarge Characteristics	ITA	SA	*inform-result*	<ITA, STA discharge characteristics>	QueryDischargeCharacteristics
M28	InformMeteoEvent	MA	RPA	*inform*	<intensity and duration of event>	RequestMeteoEvent
M29	InformMeteoEvent	MA	SA	*inform*	<intensity and duration of event>	RequestMeteoEvent
M30	QueryTreatedWastewater Characteristics	RPA	WTA	*query-ref*	<discharge characteristics?>	QueryDischargeCharacteristics

Figure A.19: Agents' messages

M31	InformSensitivity	RPA	AA	*inform*	<sensitivity type>	QuerySensitivity
M32	RequestMeteoEvent	RPA	MA	*request-whenever*	<send me meteo data; meteo event true>	RequestMeteoEvent
M33	RequestCSO	RPA	SA	*request-whenever*	<send me CSO data; when overflow true>	RequestCSO
M34	QueryIndustryDischarge Characteristics	SA	IA	*query-ref*	<IA discharge characteristics?>	QueryDischargeCharacteristics
M35	AcceptIndustryDischarge	SA	IA	*accept*	<yes discharge; conditions of agreement>	ProposeDischarge
M36	RejectIndustryDischarge	SA	IA	*reject*	<no discharge; conditions of rejection>	ProposeDischarge
M37	QueryDomestic Discharge	SA	HA	*query-ref*	<discharge characteristics?>	QueryDischargeCharacteristics
M38	QueryIndTankDischarge Characteristics	SA	ITA	*query-ref*	<discharge characteristics?>	QueryDischargeCharacteristics
M39	QuerySewerTankDischarge Characteristics	SA	STA	*query-ref*	<discharge characteristics?>	QueryDischargeCharacteristics
M40	InformSewerWastewater Characteristics	SA	WTA	*inform*	<discharge characteristics>	QueryDischargeCharacteristics
M41	RequestMeteoEvent	SA	MA	*request-whenever*	<send me meteo data; meteo event true>	RequestMeteoEvent
M42	InformCSO	SA	RPA	*inform*	<CSO characteristics>	RequestCSO
M43	InformSewerTankDischarge Characteristics	STA	AA	*inform-result*	<discharge characteristics>	QueryDischargeCharacteristics
M44	QueryDischargePrice	STA	AA	*query-ref*	<price of discharge?>	QueryDischargePrice
M45	InformSewerTankDischarge Characteristics	STA	SA	*inform-result*	<ITA, STA discharge characteristics>	QueryDischargeCharacteristics
M46	InformWWTPDischarge Characteristics	WTA	AA	*inform-result*	<discharge characteristics>	QueryDischargeCharacteristics
M47	QueryDischargePrice	WTA	AA	*query-ref*	<price of discharge?>	QueryDischargePrice
M48	QuerySewerWastewater Characteristics	WTA	SA	*query-ref*	<SA discharge characteristics>	QueryDischargeCharacteristics
M49	InformTreatedWastewater Characteristics	WTA	RPA	*inform-result*	<WTA discharge characteristics>	QueryDischargeCharacteristics
M50	SendTreatmentCost	WTA	AA	*inform-result*	<cost of treatment, €>	QueryTreatmentCost
M51	ProposeBypass	WTA_1	WTA_2	*propose*	<bypass; preconditions on the bypass>	ProposeBypass
M52	RequestBypass	WTA_1	ByM	*request*	<bypass>	RequestBypass
M53	AcceptBypass	WTA_2	WTA_1	*accept*	<yes bypass; conditions>	ProposeBypass
M54	RejectBypass	WTA_2	WTA_1	*reject*	<no bypass; conditions>	ProposeBypass
M55	RefuseBypassProposal	WTA_2	WTA_1	*refuse*	<refuse.bypass.proposal; reason>	RequestBypass
M56	AgreeBypassProposal	WTA_2	WTA_1	*agree*	<bypass; conditions established>	RequestBypass
M57	InformBypass	WTA_2	WTA_1	*inform-result*	<bypass done>	RequestBypass

Figure A.20: (cont'd) Agents' messages

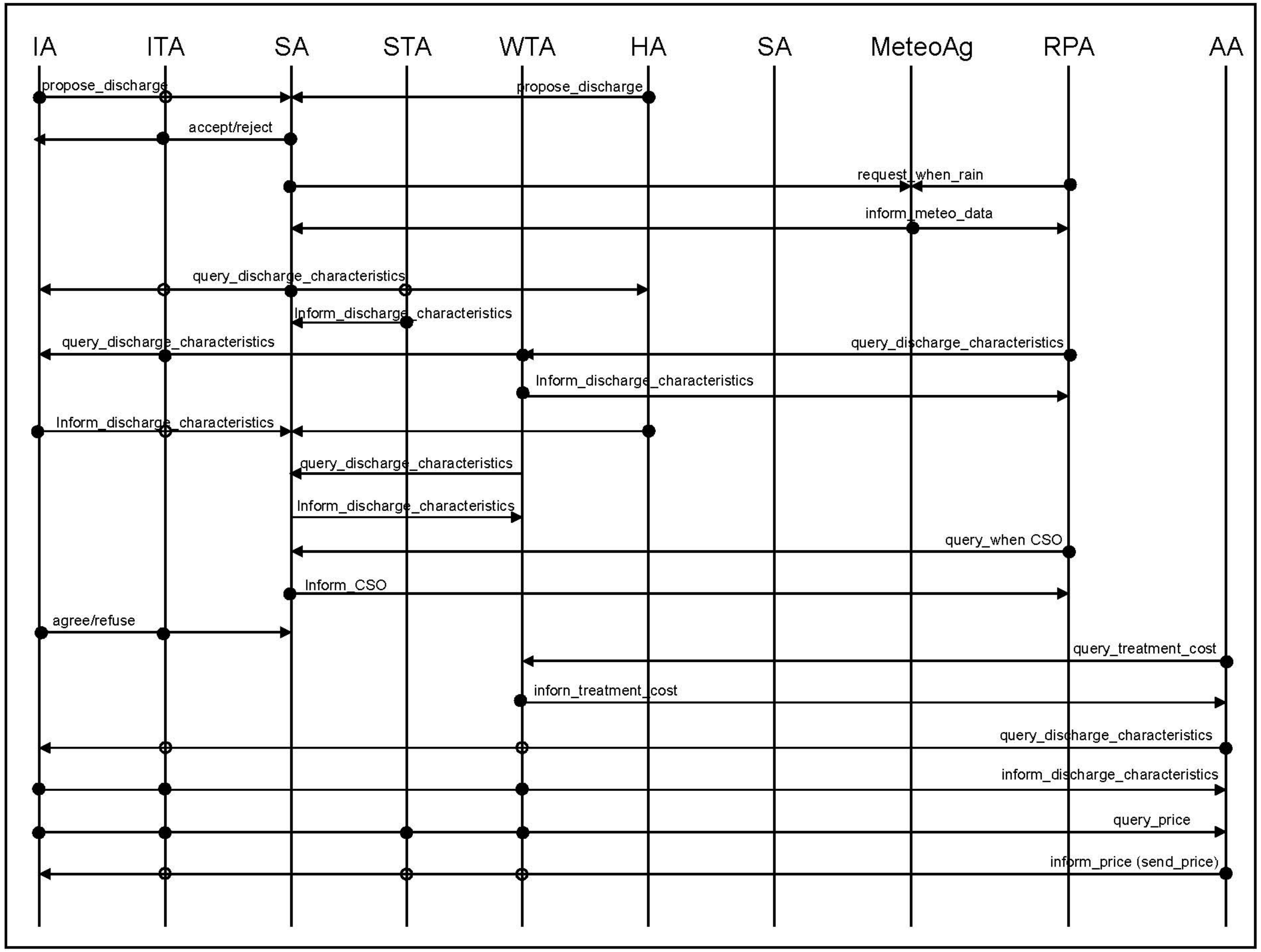


Figure A.21: Sequence diagram: is a kind of interaction diagram that shows how processes operate with one another and in what order. Basically its aim is to emphasize the chronological sequence of communication.

Appendix B

The industrial wastewater management scenario

|parse –true-negation –allow-inconsistent-answers program.sm—smodels 0
For running this program you require SMODELS system:
http://www.tcs.hut.fi/Software/smodels/

Encoding the domain independent part

```
time(0..3).
```

Encoding the domain dependent part

```
discharge_characteristics(bod5_very_high).
discharge_characteristics(pH_very_low).

wwtp_effluent(organic_polluted).
wwtp_effluent(nutrient_polluted).
wwtp_effluent(biodegradable).
wwtp_effluent(non_biodegradable).
wwtp_effluent(persistent).
wwtp_effluent(toxic).
wwtp_effluent(bioaccumulative).

wwtp_operational_situation(normal_operation).
wwtp_operational_situation(filamentous_bulking).
```

```
wwtp_operational_situation(biological_foaming).
wwtp_operational_situation(dispersed_growth).

river_situation(good).
river_situation(eutrophication).
river_situation(hypoxia).
river_situation(oxygen_depletion).
river_situation(fish_behaviour).
```

Fluents

```
fluent(d(X)) :- discharge_characteristics(X).
fluent(wwtp_eff(X)) :- wwtp_effluent(X).
fluent(wt(X)) :- wwtp_operational_situation(X).
fluent(river(X)) :- river_situation(X).
```

Actions

```
action(discharge).
action(discharge_river).
action(pre_treatment).
action(store).
action(operational_measure).
action(corrective_restoration_measure).
```

Effect propositions

```
     wt(filamentous_bulking, T + 1) :- action(discharge, T),
not wt(biological_foaming, T + 1), not wt(dispersed_growth, T + 1),
not wt(normal_operation, T + 1), d(bod5_very_high, T), time (T).

   wt(biological_foaming, T + 1) :- action(discharge, T),
not wt(filamentous_bulking, T + 1), not wt(dispersed_growth, T + 1),
not wt(normal_operation, T + 1), d(bod5_very_high, T), time (T).
```

```
   wt(dispersed_growth, T + 1) :- action(discharge, T),
not wt(normal_operation, T + 1), not wt(filamentous_bulking, T + 1),
not wt(biological_foaming, T + 1), d(bod5_very_high, T), time (T).

   wt(normal_operation, T + 1) :- action(discharge, T),
not wt(filamentous_bulking, T + 1), not wt(biological_foaming, T + 1),
not wt(dispersed_growth, T + 1), d(bod5_very_high, T), time (T).

   wwtp_eff(organic_polluted, T + 1) :- not -wt(normal_operation, T + 1),
d(bod5_very_high, T), action(discharge, T), time(T).
   wwtp_eff(organic_polluted, T + 1) :- wt(filamentous_bulking, T + 1),
not wt(dispersed_growth, T + 1), not wt(biological_foaming, T + 1),
d(bod5_very_high, T), action(discharge, T), time(T).

   wwtp_eff(organic_polluted, T + 1) :- not wt(filamentous_bulking, T + 1),
wt(dispersed_growth, T + 1), not wt(biological_foaming, T + 1),
d(bod5_very_high, T), action(discharge, T), time(T).

   wwtp_eff(organic_polluted, T + 1) :- not wt(filamentous_bulking, T + 1),
not wt(dispersed_growth, T + 1), wt(biological_foaming, T + 1), d(bod5_very_high,
T), action(discharge, T), time(T).

   river(good, T + 2) :- wwtp_eff(organic_polluted, T + 1),

   not river(oxygen_depletion, T + 2), time(T).

   river(oxygen_depletion, T + 2) :- wwtp_eff(organic_polluted, T + 1), not
river(good, T + 2), time(T).

   -river(good, T + 2) :- wwtp_eff(organic_polluted, T + 1), d(bod5_very_high,
T), not river(good, T + 1), action(discharge, T), time(T).

   -wt(filamentous_bulking, T + 1) :- action(discharge, T), d(bod5_very_high,
T), not wt(filamentous_bulking, T + 1), time(T).

   -wt(dispersed_growth, T + 1) :- action(discharge, T), d(bod5_very_high,
```

```
T), not wt(dispersed_growth, T + 1), time(T).

   -wt(biological_foaming, T + 1) :- action(discharge, T), d(bod5_very_high,
T), not wt(biological_foaming, T + 1), time(T).

   -wt(normal_operation, T + 1) :- action(discharge, T), d(bod5_very_high,
T), not wt(normal_operation, T + 1), time(T).

   action(neutralize_pH, T):- d(pH_very_low, T), time(T).
```

Executability conditions

```
exec(discharge,neg(river(problem))).
```

Initial states

```
d(bod5_very_high, 0).
d(pH_very_low, 0).
wt(normal_operation, 0).
river(good, 0).
action(discharge, 0).
```

Final states

```
finally(wt(normal_operation)).
finally(river(good)).
```

Extra code

```
hide time(X).
hide discharge_characteristics(X).
hide initially(X).
hide wwtp_operational_situation(X).
hide river_situation(X).
```

```
hide wwtp_effluent(X).
hide fluent(X).
hide contrary(X,Y).
hide action(X).
hide not_occurs(A,T).
hide not_goal(X).
hide finally(X).
hide exec(A,F).
hide executable(X,Y).
```

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