Universitat de Girona

DEVELOPMENT, IMPLEMENTATION AND EVALUATION OF AN ACTIVATED SLUDGE SUPERVISORY SYSTEM FOR THE GRANOLLERS WWTP

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TESI DOCTORAL

Development, Implementation and Evaluation of an Activated Sludge Supervisory System for the Granollers WWTP

Memòria presentada per en Joaquim Comas i Matas,
per a optar al títol de Doctor Enginyer Industrial per la Universitat de Girona

Girona, Tardor de 2000

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CERTIFIQUEN:

Que el llicenciat Joaquim Comas Matas ha dut a terme, sota la seva direcció, el treball que, amb el títol *Development, Implementation and Evaluation of an Activated Sludge Supervisory System for the Granollers WWTP*, presenta en aquesta memòria, la qual constitueix la seva Tesi per a optar al Grau de Doctor Enginyer Industrial.

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

Girona, 30 setembre del 2000

Manel Poch Espallargas Ignasi Rodríguez-Roda Layret

A la Silvia

“Of all our natural resources,
water has become the most precious. [...]
Ever since chemists began to manufacture substances
that nature never invented,
the problems of water purification have become complex
and the danger to users of water has increased.”
- Rachel Carson from *Silent Springs*

“Every individual matters. Every individual has a role to play.
Every individual makes a difference.”
- Jane Goodall

“He who asks is a fool for five minutes,
but he who does not ask remains a fool forever.”
- Proverbi xinès

AGRAÏMENTS

En el moment d'escriure aquestes quatre ratlles puc donar pràcticament per acabada la redacció d'aquest document i la finalització d'una etapa que ha estat molt important en la meva vida. Encara que soni transcendental, realment han estat dies, mesos i anys de feina i dedicació durant els quals m'han passat mil i una experiències. Quan em poso a pensar en tot aquest temps, em vénen a la memòria moltíssims records de situacions, la majoria molt bons moments, però, sobretot, me'n recordo de tota la gent que he conegut durant aquest temps o que ha estat sempre al meu costat i que m'han fet més planer aquest camí recorregut. Sense la vostra ajuda hauria estat impossible portar a terme la meva feina dia rera dia i per tant, només tinc paraules d'agraïment per a vosaltres.

En primer lloc, vull donar les gràcies als meus directors de tesi. Vull agrair especialment l'ajuda que he rebut de'n Manel, per la confiança que vas dipositar en mi anys enrera quan em vas introduir en el món de les depuradores i pel suport, orientació i clarividència d'idees que has tingut durant tots aquests anys. En segon lloc, l'altre director, l'Ignasi, al qual, a banda d'aconsellar-me sempre en els meus dubtes de feina, has estat i ets, sobretot, un gran amic. Gràcies per la teva manera d'entregar-te als amics. A en Miquel i la Marilós, principals *culpables* del camí que he seguit doncs vau ser els que em vau introduïr al món del tercer cicle. A en Jesús, company de despatx, bon amic i conseller insubstituïble de les màquines i els seus problemes. I a la Maria, amb qui també he compartit bona part de les històries del Laboratori.

També vull expressar el meu especial agraïment a l'Ulises i en Miquel de la Politècnica, als meus dos *altres directors*, pels consells, idees i hores de feina compartides. A tota la gent del Consorci per a la Defensa de la Conca del Riu Besòs però, molt especialment, al gerent, el Sr. Josep Arráez, per la seva aposta en el desenvolupament i aplicació de les millors tecnologies disponibles per augmentar la fiabilitat de les plantes depuradores i, a l'Àngel, per les hores i hores que ha dedicat en la discussió dels arbres, regles, rangs, casos....sense tu els arbres estarien desfullats. Tal com diuen les conclusions, sense la seva col·laboració i il·lusió en el projecte hauria estat impossible la realització d'aquesta feina a Granollers. També vull d'agraïr la col·laboració dels diversos caps de planta que han col·laborat en aquest treball, de l'Agència Catalana de l'Aigua, del grup Agbar, del Consorci de la Costa Brava per l'accés a l'EDAR de Lloret i del Profesor Faltings per permetre'm realitzar una estada al LIA de l'EPFL (Lausanne), i de la gent de l'Autònoma, especialment en Javier i en Juan, per les *connexions* establertes durant aquests anys. Vull agrair també, molt especialment, a l'Eugènia les hores desinteressades que ha dedicat a la part final d'aquesta tesi.

A continuació, vull recordar moltíssima gent per haver fet que la vida al Lequia, fora de l'estricta feina, hagi estat molt més agradable del que ho hagués estat sense vosaltres. Aquesta llarga llista inclou un seguit de gent que per algun o altre motiu teniu relació amb el Lequia: alguns de vosaltres ja heu acabat la tesi (Estefi, Jaumet, Luigi, Lluís i Julio J., Fredi, Joan dG, Julio W.), altres esteu pel camí (Jordi A, Núria, Elvira, i l'especial apèndix matemàtic del Lequia, en Narcís), heu finalitzat la tesina (Oriol, Jordi B, Esther, Joan Carles, Roser) o esteu a punt de fer-ho (Christian, Teia, Sònia....); altres tot just us heu iniciat en aquest món, alguns no la feu però ens ajudeu molt (diversos laborants) i una bona colla ho va deixar pel camí (Ferran, Txé, Sònia, Raül, Albert, Marta, Madel, Jordi H, Toni, Isabel). Felicitats als que ja heu acabat i moltíssims ànims als que encara us falta una mica. A banda d'Enginyeria Química i Ambiental, l'altre concepte que per mi està plenament lligat al Lequia és el de l'equip de futbol capitanejat per en Torito, als components del qual també dec el fet de poder renovar i mantenir el meu estat físic i mental. Tampoc hauria pogut acabar aquesta feina sense l'amistat i suport de tota la gent de la comuna Sant Narcisenca (Jesús i Gemma, Joan i Virgi, Xevi M, Xevi L i Mònica, Martí i Núria, Silvia, Pruni i Gemma), i als amics del Sobrequés Rafel, Jordi i parelles.

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Agraïments a banda, només em queda demanar perdó pels errors, limitacions i absències que hagi pogut tenir durant aquest anys. Heu de saber que sempre podeu comptar amb la meva ajuda, tal com vosaltres me l'heu ofert a mi. La tesi ha estat un camí llarg i difícil però els fruits que n'he tret han valgut molt la pena: a banda del treball exposat a continuació, el més important, un seguit d'experiències insubstituïbles i el naixement o enfortiment de molt bones amistats.

RESUM

La present tesi pretén recollir l'experiència viscuda en desenvolupar un sistema supervisor intel·ligent per a la millora de la gestió de plantes depuradores d'aigües residuals., implementar-lo en planta real (EDAR Granollers) i avaluar-ne el funcionament dia a dia amb situacions típiques de la planta. Aquest sistema supervisor combina i integra eines de control clàssic de les plantes depuradores (controlador automàtic del nivell d'oxigen dissolt al reactor biològic, ús de models descriptius del procés...) amb l'aplicació d'eines del camp de la intel·ligència artificial (sistemes basats en el coneixement, concretament sistemes experts i sistemes basats en casos, i xarxes neuronals).

Aquest document s'estructura en 9 capítols diferents. Hi ha una primera part introductòria on es fa una revisió de l'estat actual del control de les EDARs i s'explica el perquè de la complexitat de la gestió d'aquests processos (capítol 1). Aquest capítol introductori juntament amb el capítol 2, on es pretén explicar els antecedents d'aquesta tesi, serveixen per establir els objectius d'aquest treball (capítol 3). A continuació, el capítol 4 descriu les peculiaritats i especificitats de la planta que s'ha escollit per implementar el sistema supervisor.

Els capítols 5 i 6 del present document exposen el treball fet per a desenvolupar el sistema basat en regles o sistema expert (capítol 6) i el sistema basat en casos (capítol 7). El capítol 8 descriu la integració d'aquestes dues eines de raonament en una arquitectura multi nivell distribuïda. Finalment, hi ha una darrer capítol que correspon a la avaluació (verificació i validació), en primer lloc, de cadascuna de les eines per separat i, posteriorment, del sistema global en front de situacions reals que es donin a la depuradora

ABSTRACT

The present document wants to gather the experience obtained in the development of a Supervisory System for optimal WWTP management and control, its implementation in a real plant (Granollers WWTP) and its evaluation in the day-to-day operation with typical plant situations. This Supervisory System combines and integrates classical control of WWTP (automatic controller for maintaining a fixed dissolved oxygen level in the aeration tank, use of mathematical models to describe the process…) with the application of tools from the Artificial Intelligence field (knowledge-based systems, mainly expert systems and cased-based systems, and neural networks).

This document has been structured into nine chapters. The first part is introductory with a review of the state-of-the-art in wastewater treatment control and supervision and the explanation of the complexity of WWTP management (chapter 1). This introductory chapter together with the second one, where the antecedents to the present thesis are reviewed, are good for the establishment of the objectives (chapter 3). Next, chapter 4 describes the peculiarities and specificities of the selected plant to implement the Supervisory System.

Chapters 5 and 6 of the present document explain the work carried out to develop and build the knowledge base of the rule-based or expert system (chapter 6) and the case-based system (chapter 7). Chapter 8 illustrates the integration of these reasoning techniques into a distributed multi-layer architecture. Finally, there is a last chapter focused on the evaluation (verification and validation) of, first of all, each one of the techniques individually, and lately, of the overall Supervisory System when facing with real situations taking place in the wastewater treatment plant.

TABLE OF CONTENTS

TABLE OF FIGURES

NOMENCLATURE

AI	Artificial Intelligence	NN	Neural Networks
AS	Activated Sludge	NO_2	Nitrite
ASM1	Activated Sludge Model number 1	NO_3	Nitrate
ASM2	Activated Sludge Model number 2	NOx	Nitrate + Nitrite
ASM3	Activated Sludge Model number 3	NPC	Non-linear Predictive Control
AUR	Ammonia Uptake Rate	NUR	Nitrates Uptake Rate
Bio-P remv.	Biological Phosphorous Removal	OR	Operations Research
BNR	Biological Nutrient Removal	ORP	Oxidative-Reductive Potential
BOD	Biological Oxygen Demand	OUR	Oxygen Uptake Rate
C	Carbon	P	Phosphorous
CBS	Case-Based System	PAO	Phosphorous Accumulative Organisms
CES	Cooperative Expert System	PHB	Poly-beta-hydroxybutyrate
COD	Chemical Oxygen Demand	PI	Proportional Integral
Cond	Conductivity	PLC	Programmable Logic Controller
CSTR	Continuous Stirred Tank Reactor	RAS	Recycle Activated Sludge
DAI	Distributed Artificial Intelligence	RHOC	Receding Horizon Optimal Control
DCS	Distributed Control Systems	S	Substrate concentration
DDC	Direct Digital Control systems	SBR	Sequencing Batch Reactors
DO	Dissolved Oxygen	SCADA	Supervisory Control And Data Acquisition
DSS	Decision Support System	SPM	Simplified Process Model
EDAR	Estació Depuradora d'Aigües Residuals	SRT	Sludge Residence/Retention Time
EDSS	Environmental Decision Support System	SS	Suspended Solids
ES	Expert System	SVI	Sludge Volume Index
FIA	Flow Injection Analysis	T	Temperature
Filam	Predominant Filamentous Organism	TDHNN	Time-Delay Heterogenous Neural Network
F:M	Food to Microorganisms ratio	TDMLP	Time-Delay Multi-Layer Perceptron
GAO	Glycogen Accumulating Organisms	TDNN	Time-Delay Neural Network
GNP	Gross National Product	TDPNN	Time-Delay Probabilistic Neural Network
GSI	G2 Standard Interface	TKN	Total Kjeldhal Nitrogen
HNN	Heterogeneous Neural Network	TN	Total Nitrogen
HRT	Hydraulic Retention Time	TP	Total Phosphorous
IAWQ	International Association on Water Quality	TSS	Total Suspended Solids
IBL	Instance Based Learning	Turb	Turbidity
ICA	Instrumentation, Control and Automation	UCT	University of Cape Town
IWA	International Water Association	V&V	Verification and Validation
KB	Knowledge Base	VFA	Volatile Fatty Acids
KB-DSS	Knowledge-Based Decision Support System	VIP process	A modification of the UCT process
KBS	Knowledge-Based System	VSS	Volatile Suspended Solids
Kd	Decay rate	V30	Volume of AS settled in 30 min.
k-NN	*k*-Nearest Neighbour	WAS	Wasting Activated Sludge
Ks	Saturate Constant	WST	Water Science and Technology
MCRT	Mean Cell Residence Time	WWTP	WasteWater Treatment Plants
MLSS	Mixed Liquor Suspended Solids	X	Biomass Concentration (=MLVSS)
MLVSS	Mixed Liquor Volatile Suspended Solids	Y	Yield
μ_{max}	Maximum specific growth rate		
N	Nitrogen		
N_2	Nitrogen gas		
N/D	Nitrification and Denitrification		
NH_4^+	Ammonia		
N_2O	Di-nitrogen oxide		

1 INTRODUCTION

1.1 Environmental Degradation and Wastewater Treatment

The survival of the human species and our quality of life depend upon our ability to manage the Earth's natural resources at scales ranging from local to global. This requires an assessment of the extent of these resources, including an understanding of their variation in time and space and of what causes these variations. The excessive concentration of population at specific locations and the enormous industrialization of our society (both caused by human activity) are responsible of a non-sustainable exploitation of natural resources and the breaking of equilibrium of different natural ecosystems of our planet. It has resulted in environmental pollution, which affects negatively the quality of water, air, soil and therefore, animal, vegetal and human life. The increasing degradation of the environment has forced the society to consider changes in human behaviour for ensuring the essential conditions for the life in the Earth. This consideration has encouraged research and a great effort has been placed on understanding, preventing and correcting environmental degradation.

In this sense, the treatment of water and wastewater has become one of the most important environmental issues. Wastewater treatment is fundamental to keep the water natural resources (rivers, lakes and seas) in as high quality as possible. Not only for this environmental reason, but also due to the more and more restrictive social regulations, the correct management of wastewater treatment facilities has become very important during the last 20 years. For example, the European directive 91/271 establishes that every city or village with a population bigger than 2000 inhabitants must treat its wastewater before the year 2005, at least for the Suspended Solids (SS) and the Biological Oxygen Demand (BOD) contained in the wastewater. This criterion pursues to provide a regulated water effluent with low contaminant load to cause the minimum environmental impact (including energy use) on the quality of the receiving water ecosystem. In Catalonia, the fast implementation of this Directive by the *Generalitat de Catalunya*, according to its *Pla de Sanejament*, has given raise to the building of several WasteWater Treatment Plants (WWTPs) during the last recent years. The increase in the number of wastewater treatment facilities, to meet the ever-increasing demands of urban sprawl, involves two large capital investments:

- for their construc tion, supported by the government authorities,
- for their operation and management, supported by the operating companies.

By February 2000, the number of WWTPs operating in Catalonia were 225 (plus another 102 under construction or in an upgrading phase) and their management cost has exceeded 60 millions Euros during the year 1999.

Economics has become another critical reason for trying to optimise WWTP operation and control. Some examples of economic incentives for optimising WWTP control and management and cutting down both initial and running costs, thus increasing the efficiency in every stage of the plant are: better energy use by means of dissolved oxygen (DO) control, saving of manpower and energy, more efficient use of chemicals, better use of internal carbon in sewage for biological nitrogen and phosphorous removal, better energy use by process development (such as denitrification), interaction between design, control and operation (such as combined sewer control and plant flow control), unmanned operation during nights and weekends and, avoid consequences of malfunctioning (reservoir damages). However, more important than economics, there is the quality criteria pointed by the environmental regulations of effluent treated, which are becoming stricter worldwide. The optimal WWTP management is concerned with trying to obtain good wastewater treatment efficiency and to maintain the maximum process stability, avoiding operational problem effects.

1.2 Historical Review in Wastewater Treatment Processes

In this section, an historical review of the wastewater treatment processes from the preliminary studies to the present time will be addressed.

1.2.1 Organic Matter Removal

A typical wastewater treatment plant usually includes a primary treatment and a secondary treatment to remove organic matter and suspended solids from wastewater (Figure 1).

Primary treatment is designed to physically remove solid material from the incoming wastewater. Coarse particles are removed by screens or reduced in size by grinding devices. Inorganic solids are removed in grit channels and many of the organic suspended solids are removed by sedimentation. Overall, the primary treatment removes almost one-half of the suspended solids in the raw wastewater. The wastewater flowing to the secondary treatment is called the primary effluent [Henze *et al.*, 1997].

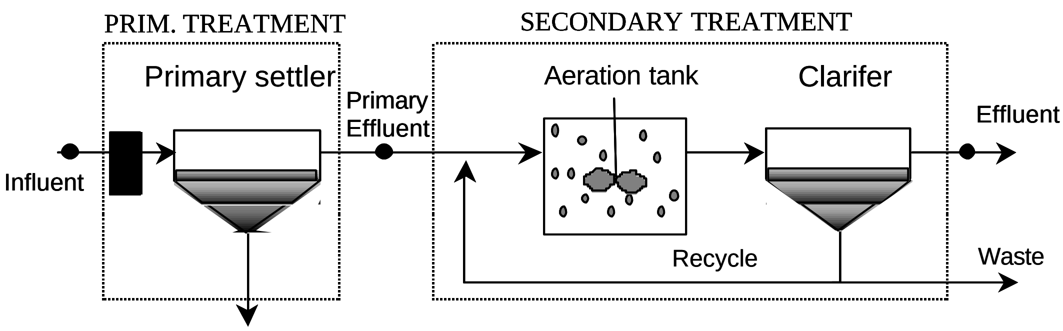

Figure 1 Primary and secondary treatment of a typical WWTP

Secondary treatment usually consists of a biological conversion of dissolved and colloidal organic compounds into stabilised, low-energy compounds, and new cells of biomass, caused by a very diversified group of microorganisms in presence of oxygen, and of the respiration of these microorganisms. This mixture of microorganisms (living biomass) together with inorganic as well as organic particles contained in the suspended solids constitutes the so-called activated sludge. This mixture is kept moving in wastewater by stirring produced by aerators, turbines or rotators, which simultaneously supply the required oxygen for the biological reactions. Some of the organic particles can be degraded by subjecting them to hydrolysis whereas others are non-degradable (inert). This mixture of microorganisms and particles has the ability to **bioflocculate**, that is, to form an aggregation called activated sludge floc if there exist a balanced population between floc-formers and filamentous bacteria. The activated sludge floc provides to the sludge the capacity to settle and separate from treated water in the clarifier. Biological reactor followed by a secondary settler or clarifier constitutes the **activated sludge process**, which is the most well known process of secondary treatment because it is also the most widely used. The biological removal of organic matter in the activated sludge process can be resumed in three reactions:

$$\text{Energy: Organic matter} + O_2 \xrightarrow{microorganisms} CO_2 + H_2O + \text{other products} + \text{energy}$$

$$\text{Synthesis: Organic matter} + O_2 + \text{energy} \xrightarrow{microorganisms} \text{new cells}$$

$$\text{Decay: Microorganisms} + O_2 \rightarrow CO_2 + H_2O + \text{energy}$$

Conversions in biological treatment plants concern basically biological growth and decay and processes of hydrolysis. Anyway, adsorption should be considered too because it may also influence the activated sludge process even if it does not concern an actual conversion. The normal operation of activated sludge process is to maintain constant a certain concentration of active biomass (measured as volatile suspended solids, VSS) to ensure a good efficiency of the wastewater treatment. The amount of biomass in the biological reactor is regulated through recycle of the suspended solids into the secondary treatment, where it is joined with the influent, and by removing the so-called excess sludge or waste (the quantity of new cell biomass produced) (see Figure 1). Therefore, organic matter that enters an activated sludge process has only 3 outlets: carbon dioxide, excess sludge or the effluent.

The use of activated sludge technology began at the end of the last century. Nowadays, this type of facilities is used widely in Catalonia. Therefore, this has resulted in a broad experience in management of the activated sludge process, as well as in design as in operation and control. From the scientific point of view, this is also the most studied process, both from the description of the processes as well as from the characterisation point of view.

1.2.2 Microbiology of the Activated Sludge Process

An important effort has been done to identify the microorganisms which are responsible of the organic matter degradation and to understand their interrelations with the overall plant performance or operational conditions. The inference of biomass state by microscopic identification of the microorganisms involved in the activated sludge process (protozoan and filamentous bacteria) can be done with the existing and recognised guides ([Jenkins *et al.*, 1993] and [Madoni, 1994]). T he identification and counting of filamentous microorganisms provide information about the settling capacity of the activated sludge and allows the identification of possible malfunctions. Additionally, it is known that the quantity and diversity of protozoan microorganisms (mainly ciliates) provide qualitative information about the performance of the biological process. They are reliable bio-indicators of effluent quality of biological aerobic wastewater treatment processes within only one hour of sampling. Changes over time in the composition of some species can predict the evolution of the plant state with enough time to carry out the appropriate action. The use of this information is an excellent means to improve the WWTP management, especially when it is integrated with the analytical results. However, sometimes it is not used because either the lack of microscope availability or the difficulty that low-skilled operators have in identifying them.

As examples of the scientific advances in this field, two recent studies are briefly commented ([Donkin, 1999] and [Tomei *et al.*, 1999]). The first one performed a statistical analysis based on factor analysis to associate specific microorganism populations with plant performance and operating conditions in a Sequencing Batch Reactor (SBR) and in continuous-flow systems. This paper signals some relationships between temperatures, dissolved oxygen, food-to-microorganism ratio (F/M), pH, the overall treatment performance and the settling ability with some filamentous bacteria and with Poly-P bacteria. Tomei *et al.* presented determinations of kinetic and stoichiometric parameters (μ_{max} and Y) for three filamentous organisms frequently detected in Italian WWTP (*Thiothrix* sp., *Microthrix Parvicella* and Type 1863) in pure cultures [Tomei *et al.*, 1999]. These parameters were utilised in a two-population model (floc formers and filamentous microorganisms) to predict the filamentous biomass fraction as the function of sulphur concentration. This study also focuses on practical information for controlling *Thiothrix* sp. proliferation. Despite these advances and the usefulness of this information to improve WWTP management, there are still few plants that make a systematic and periodic monitoring of the microbiological population and even less of them, that systematically register all this information.

1.2.3 Modelling of the Activated Sludge Process

According to Fishwick definition, to model is to abstract from reality a formal description of a dynamic system [Lein, 1997]. The characterisation of the behaviour of a system is reached by simulations. Thus, simulation[1] explains the process of conducting experiments with this model for the purpose of enabling decision makers to either: (1) understand the behaviour of the system, (2) evaluate various strategies for the operation of the system, or (3) predict possible future conditions [Lein, 1997].

Due to its high complexity, two large research lines have been established to model the activated sludge process: *Mechanistic* models and *non-mechanistic* or *black-box* models.

- *Mechanistic* models describe the whole processes taking place in the biological organic and/or nutrient removal processes, including the substrate and biomass evolution. To get this objective, different kinds of substrates and biomass are established. The relationships (stoichiometric parameters) among all these state

[1] The simulation model can be regarded as part of the background information on the system of interest, condensing existing knowledge of the structure and the dynamics of process in an organized and precise way [Lein, 1997].

variables are obtained applying the mass balances to the process. The rates proposed by the International Water Association (IWA) *Task Group on Mathematical Modelling for Design and Operation of Biological Wastewater Treatment* to model the organic matter, nitrogen and phosphorous biological removal are based on the Monod kinetics or modifications of them. Usually these models are represented in a matrix fashion (see Table 1), which should include the whole components and processes used to define the model. The IWA group proposed the Activated Sludge Model nº1 (ASM nº1, [Henze *et al.*, 1987]) many years ago, which has been internationally accepted as the model of reference for carbon and nitrogen removal. These models require a large number of kinetic and stoichiometric parameters, which should be previously adjusted, by means of a phase of calibration with experimental data. The validity of the model developed will largely depend on the reliability of the kinetic and stoichiometric parameters selected. A reliable mathematical model is an efficient way to condense data and store current process knowledge.

Processes	**State Variables**		**Velocity Rates**
	X	**S**	
* Growth +	1	$-\frac{1}{Y}$	$\frac{m_{max} \cdot S}{K_s + S} X$
* Dead	-1	-	$K_d \cdot X$
Stoichiometric parameters	Biomass	Substrate	**Kinetic parameters**
Y, yield			μ_{max} , K_s , K_d

Table 1 Matrix representation of models

- Non-mechanistic or black-box models (*i.e.* based on neural networks): these models look for modelling the plant evolution at short-term scale on the basis of the current and previously measured values of the on-line and off-line available data. In this case, the aim is not to model exactly which and how the different processes take place, but to predict the value of the variable modelled. These models present serious problems when trying to extrapolate their results to long-term scales.

Indeed, there exist in the literature different models with increasing levels of complexity in the characterisation of the activated sludge process. These existing models contribute to a better understanding of the process and represent a powerful support tool for operators and plant managers for evaluating different scenarios by experimenting in simulations. An example that models can be supportive tools is [Rouleau *et al.*, 1997] where they look for the modelling and control of a WWTP during rain events using the existing ASM1 and secondary clarifier model proposed by [Takács *et al.*, 1991]. The Water Science and Technology journal regularly publishes a volume dedicated to this field (18(6) 1985, 25(6) 1991, 31(2) 1995, 39(1) 1999), showing the evolution of the complexity of the models. Overviews of these models can be found in [Olsson *et al*., 1998], and especially for control use in [Steffens and Lant, 1999].

Some recent examples of application of mechanistic and black-box models to activated sludge processes are [Kornaros and Lyberatos, 1998], [Côte *et al*., 1995] and [Carstensen *et al*., 1998]. The first one develops a kinetic model that describes the behaviour of the denitrifying bacteria under strictly anoxic, strictly aerobic and transient conditions of growth. The second one describes a model based on neural networks to make predictions for the activated sludge process. The third one shows how a simple regression model and an adaptative black-box model, which are identified and estimated on measured data, perform significantly better than a hydrological and full dynamical deterministic flow model with many parameters (which is not identifiable and needs calibration by hand). These three models are compared according to the ability to predict the hydraulic load of a municipal WWTP for urban storm control one hour ahead.

1.2.4 Instrumentation and Control of the Activated Sludge Process

The first approach in applying certain control techniques over a WWTP was the study of the DO in the aeration tank. The DO dynamics was already examined at the middle 70s because it was early recognised that the energy needed for aeration could be considerably decreased by using the DO control. Nowadays, DO control is widely used in most of the existing full scaled plants because DO sensors are considered enough reliable from the stability and maintainability point of view [Olsson *et al*., 1998]. From a diagnostic point of view, it was also noticed of great importance to continuously estimate the oxygen uptake rate (OUR) while controlling the DO concentration [Lindberg-Carlsson, 1996a].

1.3 (Biological) Nitrogen Removal

The removal of nitrogen from wastewater by nitrification and denitrification (N/D) is a two-step biological process. In the first step (nitrification), ammonia is converted aerobically to nitrate. In the second step (denitrification), nitrate is converted to N_2O or nitrogen gas (N_2) under anoxic conditions. The coupling of these two processes results in a net loss of N to the atmosphere as N_2.

The sequential oxidation of ammonia to nitrate with intermediate formation of nitrite is conducted by two bacterial populations: *Nitrosomonas* and *Nitrobacter*. These two groups are classified as chemoautotrophic bacteria because they use inorganic carbon (carbon dioxide, CO_2) as carbon (C) source rather than organic carbon for the synthesis of new cells, and derive energy for growth from the oxidation of inorganic nitrogen compounds, primarily ammonia. Nitrifiers' cell-yield per unit of substrate metabolised is many times lower than the cell-yield of heterotrophs and denitrifiers. The two bacteria groups are differentiated by their ability to oxidise only specific species of nitrogen compounds. While *Nitrosomonas* oxidises ammonia to nitrite, *Nitrobacter* is limited to the oxidation of nitrite to nitrate. The stoichiometric equations for the oxidation of ammonia to nitrite by *Nitrosomonas* and for the oxidation of nitrite to nitrate by *Nitrobacter* are,

$$NH_4^+ + \frac{3}{2}O_2 \xrightarrow{Nitrosomonas} NO_2^- + H_2O + 2H^+ + newbiomass$$

$$NO_2^- + \frac{1}{2}O_2 \xrightarrow{Nitrobacter} NO_3^-$$

Nevertheless, other groups of microorganisms (*Nitrosococcus*, *Nitrosospira*, *Nitrocystis* and *Nitrosogloea*) have also been referenced as capable to nitrify the ammonia and other to convert ammonia to nitrite (*Streptomyces* spp., *Mycobacterium rubrum*).

The nitrification process requires a significant amount of oxygen, produces a small amount of biomass and results in substantial destruction of alkalinity through the production of hydrogen ions. According to the stoichiometry of the reactions, the conversion of ammonia to nitrate requires 4.6 g O_2/g NH_4^+. The values for biomass yield and alkalinity destruction coefficients that are generally accepted in practice for designing nitrification systems are about 0.1 g VSS produced (as nitrifiers)/g NH_4^+ and 7.1 g alkalinity (as CaCO3) destroyed/g NH_4^+. The release of free energy by the oxidation of ammonia is greater than for the oxidation of nitrite, so, as the amount of cell mass produced is proportional to the energy released, there is a greater mass of *Nitrosomonas* formed than *Nitrobacter* per mole of nitrogen oxidised. The destruction of alkalinity due to the production of hydrogen ions impacts on the aqueous carbonic acid system equilibrium, causing a drop in the pH of the nitrification reactor which, at the same time, affects the growth rate of the nitrifiers.

Denitrification involves the microbial reduction of nitrate to nitrite, N_2O and ultimately nitrite to nitrogen gas (N_2). Nitrate and nitrite replace dissolved oxygen as electron acceptor for microbial respiration in this reaction (dissimilatory nitrate reduction process). Then, denitrification is commonly thought to occur in the absence of molecular oxygen. The conditions suitable for denitrification -oxygen is absent but nitrate is present- are commonly referred to as anoxic. Since nitrogen gas is relatively biologically inert, denitrification converts nitrogen from a potentially objectionable form (nitrate) to a form that has no significant effect on the environment (nitrogen gas). Therefore, denitrifiers demand an organic substrate as carbon source and electron donor to provide energy for the process and thus are considered heterotrophs. Organic compounds found in wastewater and methanol are the two most commonly used electron donors. The overall nitrate removal (empirical) with methanol as C source can be expressed as:

$$\mathrm{NO_3^-} + \frac{5}{6}\mathrm{CH_3OH} \rightarrow \frac{1}{2}N_2 + \frac{5}{6}CO_2 + \frac{7}{6}H_2O + OH^-$$

Denitrification in wastewater systems may also provide additional benefits: the recovery of alkalinity, the reduction of oxygen demand and the production of an activated sludge with better settling characteristics. A relatively broad range of heterotrophic bacteria can be denitrifiers. More than 2000 species of bacteria can perform the dissimilatory nitrate reduction process [Henze *et al*., 1997]. Examples of denitrifiers are: *Achromobacter*, *Bacillus*, *Brevibaterium*, *Enterobacter*, *Lactobacillus*, *Micrococcus*, *Paracalobactrum*, *Pseudomonas* and *Spirillum*. Most of them are facultative: they can use either dissolved oxygen or nitrate as their terminal electron acceptor (in aerobic zones they can proliferate using oxygen and oxidising organic matter).

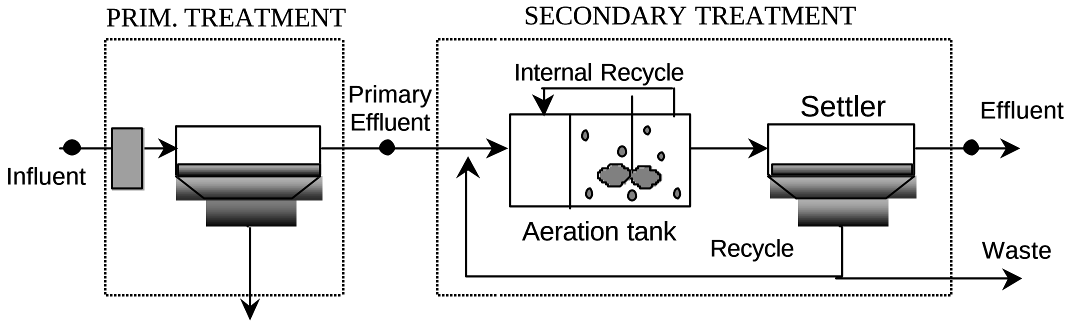

Figure 2 Ludzack-Ettinger configuration

According to the new water specifications from the European legislation, the wastewater treatment processes should include nitrogen removal in addition to BOD and SS removal. Due to this fact, the activated sludge configuration with simple organic carbon removal is becoming obsolete. These nitrogen requirements have led to a major research and development effort during the last decade for upgrading existing plants to incorporate nitrogen removal. New configurations of existing reactors and designs of new kind of reactors that allow to address the problem more successfully have arisen during last years. The most widely used configurations are based on single-sludge systems, with differences in the reactor flow type and in the anoxic/aerobic zones. For example, the Ludzack-Ettinger [Ludzack and Ettinger, 1962] or the modified Ludzack-Ettinger [Barnard, 1973] (Figure 2) are the alternative more used in adaptations of previous existing reactors while the oxidation ditch processes or the Sim-Pre process (by Envirex) are new designed reactors to remove nitrogen. Oxidation ditch processes include technologies that use elliptic reactors aerated by superficial rotators that also provide a continuous circulation path for the wastewater (see Figure 4). The Orbal process (by Envirex), or the Bio-Denitro (patented by Kruger Inc.) are examples of technologies that use oxidation ditches. The Bio-Denitro process was the first configuration specifically developed for biological nitrogen removal (early 70s), even before the legislation demands were expressed because of the high energy cost in Denmark. The implementation of nitrification/denitrification process resulted in energy savings for heavily loaded plants and to reduce acidification. In the Bio-Denitro configuration (Figure 3), anoxic and aerobic zones are created sequentially, similar to SBR, but with a continuous input and output of wastewater. The Bio-Denitro configuration requires four different phases and alternated feeding point and has no need for internal recycle (recirculation or recycle of nitrates - NO_3^- -). In contrast, a great internal recycle flow rate is needed in the Ludzack-Ettinger configuration to achieve good efficiencies in nitrate removal. For this reason, the specific designs with suitable characteristics for the N/D process are preferred over the Ludzack-Ettinger configuration in new plants, although the last one is also used. In the USA, the number of WWTPs with biological nutrient removal (nitrogen plus phosphorous) have also increased from 6 in 1984 to 250 in 1995 [Reardon, 1995].

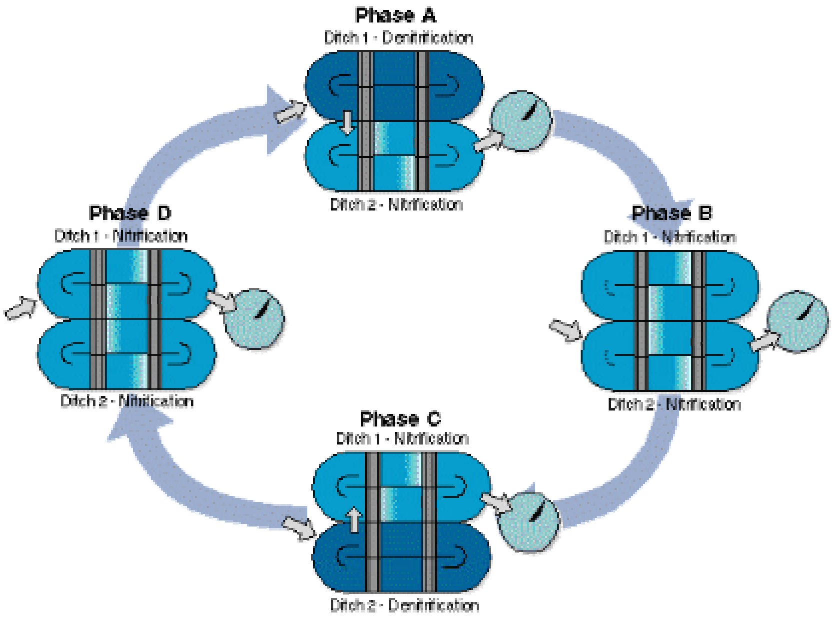

Figure 3 BioDenitro configuration for N/D (from Krüger, Inc.)

Modified Ludzack-Ettinger configuration was the progenitor of commercial configurations such as A^2/O (patented by Air Products, Inc.), Bardenpho (four-stage for nitrogen removal or five-stage for phosphorous and nitrogen removal), University of Capetown (UCT) process and VIP process.

The WWTPs may present the problem of industrial wastes with large nitrogen loads, either ammonia or nitrates. These wastes can be toxic or have inhibitory effects to the biological treatment. To deal better with nitrogen highly loaded influents, new types of reactors and configurations have been proposed. Multi-sludge systems or separate-stage nitrification systems, for example, afford some protection to the nitrifiers by the buffering capacity of the first-stage carbonaceous BOD removal process. Aside from the oxidation ditch technologies (*i.e.* the carrousel reactors), the SBRs in which sequences of aeration and anoxia are alternated to get the adequate conditions, are also widely used in N/D processes. They are very useful for small populations with high fluctuations of the influent flow rate.

Apart from those, there are other specific commercial configurations for nitrogen removal studied by the companies themselves , for example, the Sim-Pre process, Bardenpho (patented by EIMCO) or PhoStrip II (first introduced by [Levin, 1965]) processes (including phosphorous removal). There are also some studies with fixed or fluidised bed, with fixed or free biomass, that have obtained very good results in N/D removal ([Campos *et al.*, 2000], [Villaverde *et al.*, 2000], [Amer *et al.*, 1999], [Garrido *et al.*, 1998], [Fernández-Polanco *et al.*, 1995], [Gutiérrez, 2000]).

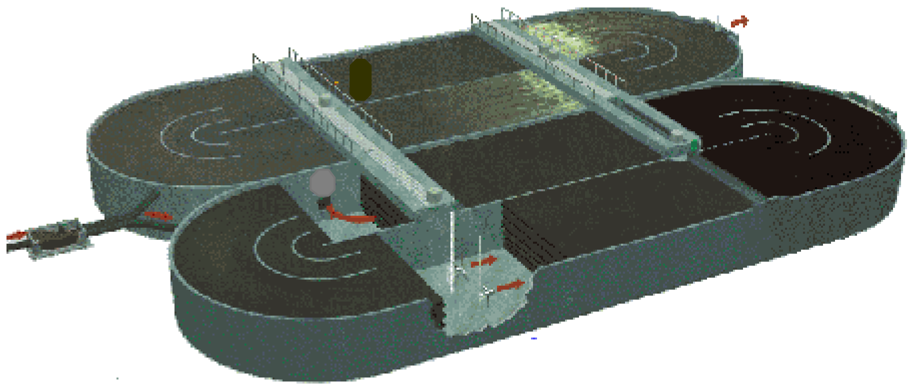

Figure 4 Oxidation ditch (from Krüger, Inc.)

1.3.1 Microbiology of the Nitrogen Removal Process

The microscopic observations do not provide enough information to know the complex community related with the N/D processes, which present co-metabolism due to the large number of nitrifying bacteria. Application of techniques from molecular biology means a deeper analysis of the bacterial communities and enables to upgrade the knowledge of these complex ecosystems [Bond *et al.*, 1995]. The application of these techniques look for the determination of the ammonia oxidisers and nitrite oxidisers activities and to study the effect of operational conditions and response in front of influent disturbances (*e.g.* toxicants) on them. The results are then related with data on the biofilm community, obtained with molecular biology techniques [Amer *et al.*, 1998]. With respect to the biological pathways of the N/D process, Van Loosdrecht and Jetten provide an overview of the possible microbiological nitrogen conversions described in the literature [Van Loosdrecht and Jetten, 1998].

1.3.2 Modelling of the Nitrogen Removal Process

As in the case of C removal, different substrates (*i.e.*, different chemical forms of nitrogen) and types of biomass are considered in their modelling. Aside from nitrification and denitrification, the conversion of organic nitrogen to ammonia nitrogen has also been considered. As mentioned previously, the ASM nº1 already includes the N/D removal. The biological nitrogen removal process has also been attempted to model with non-mechanistic or black-box models.

1.3.3 Instrumentation and Control of the Nitrogen Removal Process

In relation to the advances in the analysis of nitrogen compounds, numerous equipments have been developed to analyse ammonia, nitrate and nitrite ([Wacheux *et al.*, 1996], [Aoki and Wakabayashi, 1995]), the three parameters together ([Sorensen, 1996]), or to analyse some denitrification intermediate products ([Schulthess and Gujer, 1996]). An important aspect in the automation of these analysers is that they can work in a continuous, reliable way and with high autonomy in the biological treatment of wastewater. Nowadays, these analysers, based usually in flow techniques, are easy to use and considered quite reliable to get, in a reasonable time, information of the ammonia, nitrite and nitrate evolution, so that they can be applied for on-line control [Gabriel *et al*., 1998].

At the early stages of nutrient removal research, adequate nutrient on-line sensors were not available and, therefore, the lack of on-line measurements limited the applicability of control based on nutrient measurements. The use of ammonia and nitrate on-line sensors in the activated sludge control was first developed and documented in [Nielsen *et al*., 1981]; anyway, model-based control for nitrogen removal could not be implemented until the early 1990s when the sensors maintainability was considered sufficient [Sorensen *et al*., 1994]. Between 1985 and 1995, the activated sludge plants with alternating oxidation ditches between anoxic and aerobic stages were the most common process design and so, those were the first to be controlled. A few years later, the N/D control was adapted to non-alternating plants, *i.e*., the nitrogen control was introduced in a simple activated sludge plant. Later, the nitrogen removal control was extended to recirculating plants and supplemented with recirculation control, reducing the external carbon supply to zero. Ammonia measurements at the output of the aeration tank were used to determine the DO set point in a recirculating plant to obtain just the effluent ammonia concentration required, not the minimum, at the end of the aerated tank [Lindberg and Carlsson, 1996b].

1.4 Biological phosphorous removal

Biological phosphorous removal is quite a new process and thus, it is not so well studied as the organic matter and nitrogen removal. In this process, poly-P bacteria store large amounts of phosphorous in the form of polyphosphate granules, which are used as energy sources under stressed (anaerobic) conditions. ate, using . The energy released from poly-P bacteria under anaerobic conditions can be used to pick up substrate ("light organic molec ules" or volatile fatty acids, VFA) and store it in the form of poly-beta-hydroxybutyrate (PHB). During the aerobic phase, the stored PHB granules are used as sources of energy and for cell synthesis. Regeneration of the phosphate reserve over their metabolic requirements takes place under aerobic as well as anoxic conditions [Arvin, 1985]. It is therefore a cyclic process, see Figure 5, where the bacteria alternately release and take up phosphate. Many bacteria can carry out this process, the best known are *Acinetobacter*, and they are referred as phosphorous accumulative bacteria (PAO). Some PAOs can also denitrify [Kerrn-Jespersen and Henze, 1993].

From 1987, both Sweden and Denmark, which have always been in the forefront of the wastewater treatment field in Europe, already have very restrictive water specifications for all reservoirs (15, 8 and around 1 mg/l for BOD, Total Nitrogen –TN- and Total Phosphorous -TP-, respectively). Due to the existing plant designs and strict nutrient demands, biological and/or chemical phosphorous (P) and nitrogen (N) removal was the most cost efficient alternative. Initially in Sweden, to fulfil the phosphorous removal requirement, a post-precipitation was prescribed. Later, it was recognised that pre-prec ipitation was better than post-precipitation since a portion of the organic material was removed simultaneously, the energy needed for aeration decreased and the biogas production increased. Simultaneous precipitation was considered as another alternative. In this case, ferrous sulphate, quite inexpensive, could be used instead of, for example, ferric chloride. Lately, in the 90s, an additional effort was made to try to avoid chemical addition and instead develop and improve the reliability of the bio-P removal.

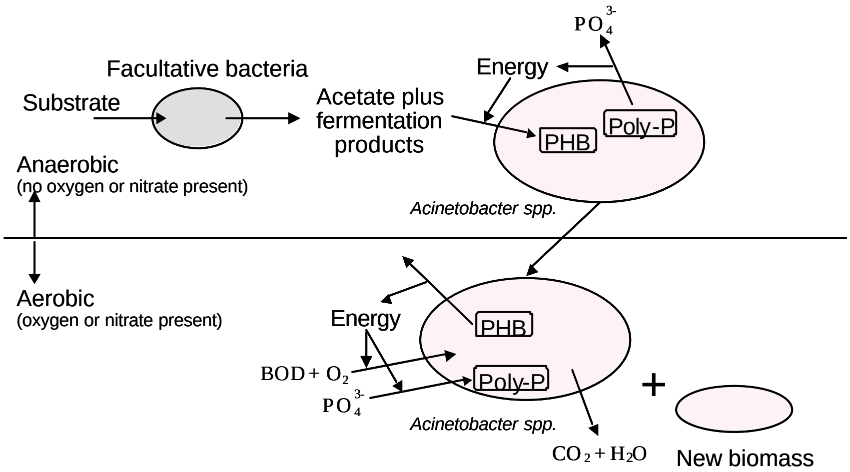

Figure 5 Phosphate transports in and out of bacteria in connection with biological phosphorous removal (adapted from [Park, 2000]).

The Bio-Denitro was extended to the Bio-Denipho process, which has the capability for both biological nitrogen and phosphorous removal (biological nutrient removal: BNR). Even though the alternating process was initially the most common process design for simultaneous BNR, diverse new configurations have been studied to optimise this process: the intermittent operation of continuous recirculating plants, various combinations of chemical precipitation, activated sludge processes with capability for biological P removal (with minimal carbon addition), two-sludge systems and sequencing batch reactors. As an example, Kiuru and Rautiainen show how two very low-loaded activated sludge plants with high biomass concentrations have been successfully upgraded to biological nutrient removal (they were initially designed as conventional low-loaded activated sludge plants with simultaneous precipitation of phosphorous), even reducing chemicals and energy costs [Kiuru and Rautiainen, 1998].

1.4.1 Microbiology of the Biological Phosphorous Removal

Among the different PAOs involved in this process, the best known according to the scientific community are *Acinetobacter*, *Pseudomonas*, *Arthrobacter spp., Aeromonas* and *Micrococcus* (Ekama *et al.*, 1996] and [Knight *et al.*, 1995]). The effect of wastewater composition on microbial populations dynamics have also been studied in biological phosphorous removal (Bio-P removal) processes [Wang and Park, 1998]. This reference points to a better phosphorous uptake rate for systems fed with acetate-containing synthetic wastewaters than for those fed with glucose-containing synthetic wastewaters.

1.4.2 Modelling of the Biological Phosphorous-removal

In the modelling of Bio P-removal, the phosphorous accumulating biomass and heterotrophic non-accumulating biomass should be considered due to the symbiosis between them. In reference to the main processes defining the PAO microorganisms, there are: VFA up taking, growth of PAO, decay of PAO, hydrolysis and generation of VFA in the anaerobic tank and the behaviour of PAO in anoxic conditions (with simultaneous nitrogen and phosphorous removal). The presence of Glycogen Accumulating Organisms (GAO) decreases the overall removal of phosphorous and hence, should also be considered.

During the second half of the 80s, the first studies describing the biochemical model of this process were published ([Comeau *et al*., 1986], [Wentzel *et al*., 1986] and [Wentzel *et al*., 1988]). These studies led to the same conclusion: this process is highly complex, not only from the microbiologic point of view but also from the operational point of view. A modification of the model ASM no.1 including the phosphorus dynamics was presented in 1995, the Activated Sludge Model nº2 (ASM2) [Henze *et al*., 1995]. In [Mino *et al*., 1997], this model is capable of predicting the behaviour of a nutrient removal activated sludge pilot plant rather well, except for the profile of ammonia (NH_4^+) and nitrites plus nitrates (NO_x^-). This paper remarks that precise calibration is essential to have good predictions and proposes procedures for the calibration of the ASM2 model. The simulation also indicates that the anaerobic rate of hydrolysis of particulate organic or slowly biodegradable substrates can be the limiting step of the organic matter removal or, sometimes, of nitrogen and phosphorous removal. The inclusion of the behaviour of PAO microorganisms in anoxic conditions (part of them are capable of nitrify and part are not) into the ASM nº2 has been published in the ASM nº2d [Henze *et al*., 1999]. Recently, it has been published the ASM nº3 [Gujer *et al*., 1999], which modifies several defects and limitations of ASM nº1.

Approaches of black-box models can also be found on modelling of simultaneous N and P removal. Three different approaches to model process dynamics (nitrogen and phosphorous) in a SBR (the ASM2 model, a simplified process model from ASM2 – SPM- and a hybrid model from the SPM and neural networks) are compared in [Zhao *et al*., 1999]. Simulation results show that the ASM2 can offer better predictions and explanations than those of the SPM. However, frequent calibrations are needed. The hybrid model from SPM and neural network shows model robustness and even improves model predictions of ASM2, making it more suitable for on-line prediction and process control.

The development of process modelling and simulation has contributed to increase the understanding of biological nutrient removal, sequencing batch reactors, settling tanks and it has also improved aeration efficiency. The three mechanistic models (ASM nº1, 2 and 3) implemented in simulation software are used to simulate off-line different alternatives or conditions in the biological treatment but the large number of parameters that are implied makes them not really useful to be included in an algorithm to control the process on-line. However, some references of nutrient removal control based on simulation exist in the literature [Isaacs and Thornberg, 1998].

The first simulation software using mechanistic models for nutrient removal was developed in the late 80s [EFOR]. Nowadays, there exist several commercial simulators for wastewater treatment processes. Among them, the GPS-X software, developed by [Hydromantis, 1995], includes all the models developed by the IWA group and some modifications of those. This and other simulators provide a user-friendly environment to conduct several studies:

- Calibrate the kinetic and stoichiometric parameters of the IWA mechanistic models for a specific plant.
- Steady state or dynamical simulations of the WWTP behaviour for scenarios with different operational conditions and influent composition
- Sensitivity analysis of any kinetic or operational parameter within the model
- To study different alternatives for upgrading or retrofitting existing WWTP from organic to nutrient removal
- enables us to evaluate WWTP behaviour in front of certain situations (at medium and long-term) and that can help to predict the possible consequences of certain actions applied over the process.

In spite of these possibilities, mechanistic models have two important limitations: they can only be used to simulate scenarios for which they have previously been calibrated; and, they fail to solve situations in which qualitative data is involved for their resolution.

1.4.3 Instrumentation and Control for Biological Phosphorous-removal

As reliable on-line sensors for phosphorous analysis were not available at the beginning of Bio-P removal (first references of on-line analysis of phosphorous include [Temmink *et al.*, 1996]), the P removal control was often supported by simultaneous precipitation. The control was then developed to enhance the biological P removal [Olsson *et al.*, 1998]. Later, it was shown that both the aeration time and the aeration volume should be included in the control to obtain an optimal biological N and P removal during large disturbances in the treatment plant [Thomsen *et al.,* 1998].

Recent studies on controlling biological phosphorous removal are focused on determining the substrate consumption rate and incorporating it into conventional controllers. As an example, Jacek Czeczot [Czeczot , 1998] proposes a model-based adaptative control of the substrate concentration in an aeration tank using the wastewater level as the minimal-cost control of the modified activated sludge process. The adaptative controller is based on the substrate consumption rate and acts on the flow rate coming from the aerator tank. The substrate consumption rate is estimated on the basis of the least-square method. This paper proves that co-operation of the DO conventional controller with this adaptative controller of the substrate concentration allows the process to be operated at minimum costs (low consumption of aeration energy).

Large efforts have been placed on the development of reliable nitrogen and phosphorous analysers, and there has been a lot of progress in the instrumentation technology. In this sense, an instrumentation test has been designed to test the reliability of on-line analysers using a carefully prepared protocol that has been reviewed by the own manufacturers [Truett Garret, 1998]. Many interesting instrumentation advances, already commented in this thesis, are reviewed in [Briggs, 1998]. The development in sensor technology has resulted in an increase of available data, which, unfortunately, has not always been corresponded to an increase of information. The extraction and integration of adequate information from several sensors for fault detection and diagnosis is not an easy or trivial task. In this sense, Rosen and Olsson in [Rosen and Olsson, 1998] presented different tools for detecting unusual on-line measures and deviating process behaviour (*e.g.*, to examine the variance of a raw signal, multiple process data, Principal Component Analysis, Partial Least Squares...).

Commercial advanced control systems (like STAR control) were introduced in the mid 90s to optimise effluent quality, energy and chemical usage [Nielsen and Onnerth, 1996]. Nowadays, although advanced instrumentation enables a reliable control based on on-line measurements, most of the facilities do not have on-line sensors for nutrient content yet, and the plants that already have them, usually use them for monitoring purposes rather than for automatic control.

1.4.4 Sedimentation

In the biological treatment of wastewater, the sedimentation process enables to separate the treated wastewater from the biomass sludge and produces a clear treated effluent. In addition to clarification, secondary settler tanks or clarifiers have the function of thickening the activated sludge for returning to the bioreactor and even, as storage tank. The settling process can take place in the same reactor (SBR) or in a secondary settler. Settling problems are mainly associated to hydraulic loads or sludge characteristics (arise from an unbalanced composition of the bacterial community and from the excessive proliferation of filamentous bacteria). So, the identification and monitoring of these bacteria is critical to estimate the settling capacity of the activated sludge. By all these reasons, secondary settling tanks have been considered essential and often they can be limiting factors for good removal efficiencies of the activated sludge system. Tákacs and assistants developed the first model of settling process that can consider or not possible biological reactions in the clarifier [Tákacs *et al.*, 1991]. Simulation of sedimentation has enabled a better understanding of the settling tanks. Recent studies are dedicated to design, model and operate clarifiers ([Ekama *et al.*, 1997], [Yee-Chung *et al.*, 2000] for primary settlers).

1.5 State-of-the-art on WWTP process control

In the early 70s, some devices were installed in the plants to monitor the plant conditions. These devices were able to log data and display the status of the plant on large mimic boards. Later, the proven reliability of computer systems and control loops led to monitors with very good display systems, and to the inclusion of automatic or remote process control and operation of the essential operational valves and other control equipment. This improvement was particularly helpful in large plants. Real operations can be carried out directly from the control computer. Computers are capable of retrieving almost instantaneously numerical data, visualised graphics, and process flow and instrumentation diagrams from the different databases and of displaying all these data. [Ohto, 1998]. In reference to communication, the transmission of information is evolving to ultra high-speed, high capability, and high reliability, digital and unified network communications. For example, Ohto evidences that the installation of optical fibre cable network within the sewer will allow the remote control of a pumping station and of a sludge treatment facility and the exchange of information between treatment plants. Internet can also be used today for data acquisition from various plants and also for remote control [Baeza, 1999].

As mentioned, research and progress in instrumentation, monitoring, modelling and computer technology has enabled automatic process control improvement. This section introduces some advanced **classical automatic control** trends applied to wastewater treatment plants. Classical current control trends include instrumentation and control devices integration (**distributed** control), **multivariate** control, **optimal** control and **hydraulic** capacity control. They are briefly explained:

1. *Distributed control:* This advanced control allows to keep the plant running by a large number of local controllers for physical variables, like liquid, sludge and air flow rates, levels and pressures. Control elements have progressed from direct digital control systems (DDC), distributed control systems (DCS), programmable logic controllers (PLCs), to the use of PC along with PLCs or I/O boards in minimal systems. Each control element is responsible of the element situated hierarchically below its control. The maximum quantity of knowledge about the process (and the maximum capacity of decision) is supplied to each one of the different levels of control. This complex control system (distributed control systems by PLCs), usually implemented as Supervisory Control And Data Acquisition (SCADA) systems provides a robust control over the process faults (becoming more fault tolerant) and enables supervision of the system.

2. *Multivariable control*: Extensive reviews on activated sludge control reveal that most of the studies on these issues have some limitations [Steffens and Lant, 1999]: (1) apply only to conventional carbonaceous pollutant removal systems; (2) are focused on the control algorithm more than on the structure of the overall control system; (3) almost all the studies focus on controlling variables with fast response dynamics (flow or DO) or on secondary process variables such as Sludge Residence Time (SRT), Mixed Liquor Suspended Solids (MLSS) and OUR, but very few studies focus on controlling the real process objectives (effluent quality, variables with slow response dynamics); and (4) lack on the use of multivariable systems. For these reasons most recent studies consider: (1) the control of BNR processes from a multivariate perspective emphasising the complex, non-linear and time varying relationships between inputs and outputs, and (2), try to control variables with medium response dynamics (effluent Chemical Oxygen Demand –COD- and nutrient concentrations). Some studies presenting multivariate control strategies for activated sludge processes include [Dochain and Perrier, 1993], [Youssef *et al*., 1995], and more recently, [Lindberg, 1998] and [Steffens and Lant, 1999]. Lindberg developed a linear multivariate time-invariant state-space model and applied it to a multivariable linear quadratic (LQ) controller to control the ammonia concentration in the effluent.

Steffens and Lant evaluated five different multivariable model-based control algorithms to control nitrogen removal in activated sludge processes. The ASM1 model was used to model the biological kinetics and three different disturbance scenarios were considered to facilitate controller evaluation: step in feed Total Kjeldhal Nitrogen (TKN) concentration (from 50 mg/l to 70 mg/l), one set of real influent data from Brisbane WWTP and an artificial ammonia impulse and a 50% increasing in feed flow rate. Proportional Integral (PI) controller does not always meet the total nitrogen limit whereas non-linear predictive control (NPC) performed the best of any control algorithm.

3. *Optimal control:* recent studies on N/D processes focus on the optimisation of design and operation ([Ayesa *et al*., 1998] and [Furukawa *et al*., 1998]) and control [Lukasse *et al*., 1998]. The first one presents an optimisation algorithm to select the design and the operational parameters in activated sludge processes. The algorithm automatically estimates the dimensions and operating point of the plant that minimise a global penalty function by combining effluent requirements and costs. The first version of this algorithm was oriented to the optimum design and operational activated sludge reactors including N/D, and it has been incorporated into simulation software. The second one ([Furukawa *et al*., 1998]) developed a support system to estimate which is the optimal ratio between aerobic and anaerobic zone length and retention time (it was found to be equal to 1). The third one ([Lukasse *et al*., 1998]) introduces an optimal control of N-removal in the activated sludge processes. This study deals with the development of an aeration strategy yielding optimal N-removal in continuously mixed, continuously fed activated sludge processes. First, optimal control theory was applied to the ASM1 model, showing that both alternating nitrification/denitrification and simultaneous nitrification/denitrification at limiting DO-levels might be optimal but they selected the first option because they accounted for the risk of sludge bulking at limiting DO-levels. A *Receding Horizon Optimal Control* (RHOC) strategy using NH_4^+ and NO_3^- measurements, which enables feedback control was developed. This controller has successfully passed several tests both in simulation and in a pilot plant.

4. *Hydraulic capacity control:* One of the major topics in control during the last few years has been the hydraulic capacity of the plants, by means of the control of sludge retention in aeration tanks during peak hydraulic loads. This wastewater treatment hydraulic control is used in combination with the sewer system control to reduce the higher demand that could arise from the storm water discharges [Olsson *et al*., 1998]. The BNR processes are more sensitive to flow variations, especially with regard to sludge loss from secondary clarifiers (washouts). To alleviate the problems caused by inflow variations into the plant, the application of this real time integrated control of sewer and wastewater systems does not require large investments since storage volumes should not be erected. Available aeration tanks and clarifiers are used for storage of storm water or for redistribute activated sludge.

The 1997 *Instrumentation, Control and Automation* conference included several papers discussing the application of advanced controllers [ICA, 1997]. The problem with the implementation of multivariate, optimal and hydraulic capacity control in BNR strategies is that they require a large number of on-line determinations (*e.g.*, dissolved oxygen, oxidation-reduction potential – ORP -, ammonia nitrogen, nitrate nitrogen, total nitrogen and total phosphorous, the automatic control of aeration, circulating water flow, Recycle Activated Sludge – RAS -, Waste Activated Sludge – WAS -, coagulant dosage and ozone dosage rate), which usually are not available in the majority of WWTPs. On the other hand, most of the WWTPs are beginning to have an SCADA that implements a distributed control system through a PLC network.

Although the scientific community has exhaustively studied wastewater treatment processes from the instrumentation, modelling and control point of view over the last 20 years to accurately control WWTPs, their optimal management remains still unsolved. The optimal management and control is difficult due to the multi-faceted nature of any complex system (*e.g.* environmental processes), which involves many physical and (bio)chemical processes. Next section introduces the special features that make environmental processes in general, and specifically, biological wastewater treatment, so difficult to manage efficiently.

1.6 Management of environmental processes

Environmental processes are complex systems, involving many interactions between physical, chemical and biological processes, *e.g.* chemical or biological reactions, kinetics, catalysis, transport phenomena, separations, etc...The successful management of these systems requires multi-disciplinary approaches and expertise from different social and scientific fields. Some of the problematic and special features of environmental processes are described in [Guariso and Werthner, 1989]:

- Intrinsic unsteadiness: most of the chemical and physical properties as well as the population of microorganisms (both in total quantity and number of species) involved in environmental processes do not remain constant over time. On the contrary, these processes evolve over time. For example, in the wastewater treatment processes, the characteristics of the influent can be highly variable both in quantity (flow rate) and in quality (concentrations) and there are different changing inter-relations between substrates and microorganisms. This means that the often-assumed stability of these systems is wrong in many cases.

  Additionally, at a different time scale, typical influent wastewater composition is also changing in societies under development. Economic and cultural changes influence wastewater composition. The BOD loading per capita and the wastewater temperature increase with increasing per capita Gross National Product (GNP). Some of the factors that may influence wastewater characteristics are culture cooking, development of new industrial products, water savings and reuse, type of detergent, better sewer networks…[Henze, 97]. Recent studies demonstrated that wastewater composition has a strong influence on processes of the treatment plants. In this sense, [Andreadakis *et al.,* 1997] propose to carefully study the performance of BNR systems based on wastewater characterisation before designing biological reactors. This approach avoids having under-designed reactors that are based only on standard nitrification and denitrification rates. In this study, they examined the possible impact of toxic inflows (high salinity and industrial contributions to the total wastewater flow) on nitrification by means of ammonia uptake rate (AUR) and nitrates uptake rate (NUR) tests. Besides, influent composition is not exactly known since pollutant concentrations are only measured with global variables (COD or BOD for organic matter), instead of measuring each one of the organic substances of wastewater.

- ill-structured domain: environmental systems are poor or ill structured domain, that is, they involve knowledge difficult to clearly formulate due to its high complexity. Many facts and principles underlying environmental domain cannot be characterised precisely in terms of a mathematical theory or a deterministic model whose properties are well understood. The experts of environmental processes possess this *heuristic* knowledge, which represents: a) the subjective decision-making exhibited by experienced engineers in fulfilling the requirement of a given process, b) a way of combining information of different kinds that cannot be expressed with mathematical modelling. In wastewater treatment, this heuristic knowledge enables plant managers to identify certain states of the plant and to solve any problem based on previous experiences.

- Uncertainty and imprecision of data or approximate knowledge and vagueness: many environmental systems are stochastic. The parameters used in models defining such processes are usually uncertain, and their operational ranges are only known approximately. People use linguistic qualifiers that act over concepts or values that are difficult to capture and represent [Beltramini and Motard, 1988]. Most of the information available in environmental processes involving biological reactions is qualitative and difficult to translate into numerical values.

In the case of WWTP, there is a complex population community that evolves with time since it adapts to the process and influent characteristics. The microbiological information obtained from microscopic observations of the activated sludge (*i.e.*, presence and abundance of the microfauna - protozoan and metazoan - and presence and abundance of filamentous and floc-forming bacteria referred with symbolic expressions as *none, few, some, common, abundant, excessive*) and other qualitative data as any *in-situ* observation of the plant or V30-settling test observations taken by operators or plant manager (*e.g.* effluent appearance, colour and odour of wastewater, presence of bubbles or foams in the reactor/settler surface, cloudy supernatant on V30-test...) are crucial for the correct management of the plant, specially taking into account together with analytical and on-line determinations. This qualitative information is essential, but it is not suitable to include in the context of a classical numerical control model.

As mentioned before, the use of on-line analysers is still scarce and they often are unreliable. In Catalonia, the most widely used on-line process data includes dissolved oxygen, temperature, pH and water and sludge flow rates. These data are not enough to monitor and diagnose the process successfully, it is necessary to be able to access more information. Most of the variables describing the process are global and cannot be obtained on-line but with delay of some hours or days (as the global indicators of organic matter COD or BOD). There is also a high incidence of missing information which biases wastewater-treatment analysis.

- Huge quantity of data/information: the application of current computer technology to the control and supervisory elements for these environmental systems has led to a significant increase of amount of data acquired (improved SCADA equipment enables to acquire large quantities of data). However, such an increase in either frequency, quality, quantity or diversification (quantitative as well as qualitative) of data of the same process not always corresponds to a similar increase in the process understanding and improvement. Specifically in the WWTP domain, the mountains of data that present-day, computer-controlled plants generate, must be used by experts to carry out the following tasks: distinguish between normal and abnormal operating conditions, identify and evaluate the factors influencing process trends (*e.g.*, external load disturbances, equipment faults...), anticipate future operational states and plan and schedule sequences of operating steps to bring the plant at the desired operating level. Nevertheless, the volume of data is so high that it is not an easy task for process experts to acquire, to integrate and to understand all this day-to-day increasing amount of information.

Heterogeneity and scale: because the media in which environmental processes take place are not homogeneous and cannot easily be characterised by measurable parameters, data is often heterogeneous. For environmental real world problem, data comes from numerous sources, in different format, frequency and quality. In fact, an exhaustive list of factors influencing the usefulness, quality and validity of environmental data include: information type (describing the format and form), availability (explaining the relative ease of access and location of information), timeliness (concerning the speed at which information can be delivered to the decision maker), accuracy (expressing the reliability of information and the level of error or uncertainty it contains), and cost (defining the "price" of information expressed in an economic sense and from a human resources, time investment perspective). Besides, environmental systems involve physical processes which take place in a 2- or 3- dimensional space. Thus, sometimes there is a strong spatial distribution involved.

Focusing on wastewater treatment processes, four different types of data can be identified in WWTPs: on-line quantitative, off-line quantitative, qualitative observations of plant operators and microscopic observations. Besides, these data correspond to measures with different time-scales due to the different frequency of analysis. For example, the analytical results of some parameters present delays of minutes, hours or even days while other on-line data are updated every few seconds.

In addition to the special features of environmental systems already explained, wastewater treatment processes, especially biological processes, have additional particular features from the standpoint of control that make them even more difficult to control and supervise using a single conventional strategy, with respect to any other environmental process. Particular characteristics of wastewater treatment processes are:

- Non-linearity: the reactions of the activated sludge process often reach pseudo-stability when substrates, nutrients or oxygen are limited. The system remains in the non-linear operation state space, which is often represented by the Monod equation, and this makes the application of modern control more difficult [Ohtsuki *et al.*, 1998].

- There is a lack or paucity of knowledge in the understanding of the process mechanisms and so, a large dependence on empirical knowledge: detailed knowledge of the treatment process is limited and theoretical understanding of biological phenomena such as bulking or foaming is still poor. Therefore operators usually rely on their empirical know-how to solve problems.

- The need to always maintain the effluent specifications to minimise the impact over the recipient medium. Moreover, the legal regulations of the wastewater effluent have varied over time. Some years ago the performance of the WWTP was based on the organic matter (BOD and COD) and suspended solids removal. Nowadays, nutrient removal is also considered as specified in the legislation of effluent quality standards (the 91/271 European directive). This is especially important in zones considered to be sensitive where effluent nitrogen and phosphorous concentrations are limited to a legal value. These new considerations largely affect wastewater management. At this moment, the simplest biological treatment of the activated sludge process (consisting in a reactor where microorganisms and wastewater are mixed and aerated and a secondary settler) is not enough to cope with these new standards. We should consider all the biological processes and their interrelations involved in the biological nutrient removal and supply aerobic, anoxic or anaerobic conditions, according to the process.

- Change in control objective: usually the control objective of a wastewater treatment facility is the treatment efficiency from the standpoint of effluent water quality but it may change in some special conditions, *i.e.*, in episodes of storms weather or inhibition of biological activity.

- Trends on the variables: to get some more information about the state of the process, to know the trends of some variables rather than punctual values is becoming increasingly important. In this sense, respirometers have been developed and, nowadays, some of them are used on-line to identify variations in the OUR, allowing to identify variations in the state of the biomass faster than the analytical results ([Ning *et al.*, 2000], [Spanjers and Vanrolleghem, 1995] and [Temmink *et al.*, 1993]). This fact, for example, could help identifying organic or toxic shocks faster than the methods used before.

1.7 Artificial Intelligence Contribution

All these special characteristics of wastewater treatment processes have led to an even deeper research to improve their control and management. Approaches other than a straightforward application of conventional control theory are needed to look for the optimal management of complex processes when the process state is far from its optimal operation and reasoning with qualitative information is essential to deal with problems.

1.7.1 Intelligent control

Due to the complexity of wastewater treatment process control (because of different reasons already explained), even the most advanced conventional *hard* control systems have encountered limitations when dealing with problem situations that require qualitative information and heuristic reasoning for their resolution (*e.g.* presence and interrelations among different microorganisms, substrate and operational conditions in filamentous bulking problem, foaming…). Indeed, to describe these qualitative phenomena or to judge circumstances that would need a change in the control action, some kind of linguistic representation built on the concepts and methods of human reasoning, such as intelligent systems, was necessary. And this is the reason why human operators have, until now, constituted the final link for closed-loop plant control [Manesis *et al.*, 1998]. It was necessary a deeper approach to overcome the limited capabilities of conventional automatic control techniques when dealing with *abnormal* situations of complex systems, and to provide the level and quality of control necessary to always satisfy the environmental specifications. For these reasons, the discipline of **intelligent control systems** appeared as a promising field to solve these problems a few years ago and since then it has had a significant impact in the process industry.

The intelligent control term is applied to a control system, which uses fuzzy logic, knowledge-based or/and neural networks. It denotes a controller with the following features [Stephanopoulos and Han, 1996]:

- in addition to numerical algorithms, it also uses logic, sequencing, reasoning, or/and heuristics
- it is essentially a non-linear controller possessing autonomy which is broader than that of conventional controllers
- to carry out its expanded functionality, it relies on representational forms and decision-making procedures, which emulate paradigms assumed to be in human/biological systems.

The intelligent control techniques can be divided into knowledge-based and soft computing techniques (neural networks, genetic algorithms and fuzzy logic). Knowledge-based systems (KBS) comprise several Artificial Intelligence (AI) techniques, which involve reasoning with some kind of knowledge (heuristic on expert systems, experience on case-based systems…) to solve a problem. Some of the problems with conventional control systems have been the focus, during last years, on much of the research effort in AI, especially in KBS.

1.7.1.1 Knowledge-based systems

Knowledge-based systems have shown promising results due to its capabilities on representing heuristic reasoning and on working with large amounts of symbolic, uncertain and inexact data, and qualitative information which human operators comprehend best. Conventional or classical control methods cannot deal with these tasks. Thus, KBSs permit implementation of human-like control strategies, which have hitherto defied solution by any of the conventional *hard* control techniques. KBS enables us to take advantage of the experience gained by the experts from years of operation and to build new *models* capable of describing better the knowledge of the biological processes. Expert Systems (ES), defined as intelligent systems that use rules to encode expertise, are the core of this class of intelligent systems. ES use linguistic rules or conditional statements elicited from human experts, which when chained in logical sequences could affirm or disprove a given conclusion, or generate a new situation. Another intelligent technique widely used is Case-Based Reasoning, which reuses results and experience from previous particular situations that have affected the process performance to solve the current problem. Thus, using this technique is possible to solve brand-new situations similar to previous ones with less effort than with other methods, which start from scratch to build up new solutions [Kolodner, 1993]. Case-Based Systems (CBS) have been used recently in several fields such as planning [Champati *et al.*, 1996], fault diagnosis, medical detection, design [Maher and Garza, 1997], or alternative selection [Kraslawski *et al.*, 1995], due to their optimal results and to their relative easy development; however, they have received less attention in the (bio)-chemical engineering domain.

It represents an effort to gather all the amount of data generated by the plant and sometimes we do not take advantage of that because we do not know how to interpret or use such volume of information. A part from a statistical analysis, it would be important to take more benefit from the historical database. KBSs provide efficient tools (manual or automatic knowledge acquisition techniques - see chapter 5 -) to extract useful information from the increasing amount of data available. They are able to identify and capture the key parameters controlling the complex systems. This contrast with the classical techniques which could not provide sophisticated structuring and organisation to face the task of finding the most relevant information. The knowledge extraction or acquisition phase aims to discover the knowledge implicit in the data in order to facilitate or increase the process knowledge acquisition. There is a lot of information in the databases that can only be detected relating the data within themselves (*expert knowledge*, *e.g.*, [Patry and Chapman, 1989]) and within their previous values (*temporal* or historic *knowledge*). The identification of the relationships among different operational conditions or among the variables characterising that situation is very important both for the identification and for the prediction of problems (called *causal reasoning*, *e.g.*, [Sobel, 1993]). Moreover, the historical information about common problem situations or cases lived by the plant manager and the solutions adopted to try to solve them (called *experiential knowledge*) are also very important to improve the WWTP management and supervision and to implement learning tasks of a supervisory and control system [Sànchez-Marrè *et al.*, 1997a]. An exhaustive analysis of the data is needed to get a deep and complete understanding of the state of the process, otherwise, only a superficial vision of the state of the process will be gained. Several techniques of AI have been proposed to conduct the data analysis ([Ozgur and Stenstrom, 1994] , [Ladiges and Kayser, 1993] and [Krichten *et al.*, 1991]).

The most successful KBSs have been those specific to a narrowly defined problem, which are scalable to a continuously expanding knowledge base, and which integrate diverse sources of requisite knowledge. Several KBSs have been, more or less successfully, developed in the wastewater treatment area, most of them as off-line consultations or as a decision aid for very specific problems:

- diagnosis ([Lapointe *et al.*, 1989], [Gall and Patry, 1989], [Krichten *et al.*, 1991] and [Bergh and Olsson, 1996]),
- design ([Krovvidy *et al.*, 1991], [Krovvidy and Wee, 1993] and [Hudson *et al.*, 1997]),
- as a decision aid ([Maeda, 1985], [Maeda, 1989], [Patry and Chapman, 1989], [Okubo *et al.*, 1994] and [Yang and Kao, 1996]),
- operation ([Barnett, 1992], [Barnett *et al.*, 1993], [Ladiges and Kayser, 1993], [Serra *et al.*, 1994], [Zhu and Simpson, 1996], [Cabezut-Boo and Aguilar, 1998], [Furukawa *et al.*, 1998], [R.-Roda *et al.*, 1999b] and [Urueña *et al.*, 1999])
- process optimisation ([Huang *et al.*, 1991])

With respect to process control tasks, knowledge-based **expert control systems** are widely used in a broad range of applications (controller tuning and adaptative control, selection and configuration of PLCs, design of multivariable controllers…). Some approaches in the literature rise with expert process control of wastewater treatment processes ([Capodaglio *et al.*, 1991], [Couillard and Zhu, 1992] and more recently, [Isaacs and Thornberg, 1998]). However, some developers of knowledge-based expert control systems have recognised that rule-based systems are quite fragile or brittle because their scope is limited to the forecasted situations in the domain and they are not reliable when applied to unexpected situations. Due to this fact, developers of knowledge-based control systems have kept expert systems outside the control loop, leaving this task to proven algorithms or the discretion of the human operator. Moreover, Olsson [Olsson *et al.*, 1998] suggested that expert system control did not finally prevailed because they were too complex and the available knowledge could not be captured into the KBS in reliable models to control the process.

1.7.1.2 Soft-computing

On the other hand, some examples of intelligent systems that have been applied with success in control algorithms and embedded in PLCs are the so-called ***soft computing*** techniques. These techniques, such as fuzzy logic and artificial neural networks, have been proven in the control loop providing good results. In fact, a fuzzy controller for the cement industry was the first intelligent control system implemented in the process industry and today such controllers are applied to control hundreds of industrial plants worldwide. Fuzzy control is in essence rule-based control but without the brittleness of the expert controllers, that comes from the sharp delineation of the quantified descriptions. In *soft* control, knowledge of the process dynamics is not essential. Their application in the process industry has led to significant improvements in product quality, productivity and energy consumption [Manesis *et al*., 1998]. Now it is firmly established as one of the leading advanced control techniques. Some examples of successful fuzzy and neural net controllers to wastewater treatment plants can be found in [Hunt *et al*., 1992], [Kosko, 1992], [King, 1997], [Bow-C, 1998], [Manesis *et al*., 1998] and [Huang and Wang, 1999]. However, some researchers fear that even neural networks will not reach success either in wastewater treatment control due to the need of obtaining interpretable parameters [Olsson *et al*., 1998].

The current trend in control is based on reviewing the conventional models (based on mathematical computations) and the intelligent ones (based on fuzzy, neuron and knowledge); and the challenge is to simplify them as far as possible and to combine them into one (as for example in [Zhao *et al*., 1999]).

1.7.2 Process Supervision: Integrated Intelligent Systems

One step forward in the optimal management of complex systems, like wastewater treatment systems, should involve a **supervision** at a higher level to monitor, evaluate, diagnose these systems, actuate over the system (adapting the control algorithm or implementing an expert action), and finally, to provide a faster problem detection and solving procedures and ensure the optimal treatment efficiency in abnormal as well as normal situations. In fact, KBSs have found the most extensive applicability as **Supervisory Systems**. The advanced approaches of KBSs in supervisory control have been proved in the practice and have provided handsome economic returns. This supervisory control in industrial applications includes complex control schemes, recovery from extreme operating conditions, emergency shutdown, de-bottlenecking of process operations and heuristic optimisation. Nevertheless, the optimal higher-level supervision can only be achieved with an integration of several forms of knowledge representation (mathematical modelling, knowledge-based, soft computing…). This section explains the steps taken on the evolution of complex process management from single to integrated techniques, defines what are integrated intelligent systems, introduces how these systems are implemented and gives some examples of application.

Most researchers have long been concerned with investigating of how a single technique can function successfully based on a diagnostic or numerical reasoning to supervise complex problems. However, the application of a single conventional, a single knowledge-based or a single soft-computing technique also presents some limitations because real problems are too complex or risky to be handled by individual systems, and therefore, is limited in solving real world problems. In contrast, most real world problems require interdisciplinarity. Also, Avouris pointed out that the reason that there are still a limited number of Expert Systems for environmental applications can be found in the erroneous **individual** use of KBS techniques [Avouris, 1995]. On the contrary, he pointed out that a new field of cooperative Expert Systems can enable successful use of ES technology in many environmental applications. Some of the pitfalls that are only solved partially with the individual use of an intelligent approach are: (1) the limitation of its scope to the forecasted situations in the domain (*i.e. brittleness*); (2) most of the KBSs do not learn from their experiences; (3) the bottleneck of the knowledge acquisition; (4) the low sharing and reusability of knowledge bases; and (5), the lack of knowledge introduced in neural networks and the lack of explanation of the results from neural networks.

Thus, one expects that multiple systems working in a distributed computation environment could increase the quality of KBS and handle more complicated problems because one of the characteristic features of an intelligent system is its ability to utilise a wide range of data and modelling methods just like human *intelligent* activities do [Rao *et al.*, 1998]. These multiple systems exhibit a higher level of complexity, sometimes have to cope with problems on the border (or slightly outside) of their particular domain of competence (robustness) and have to be properly self-updated and maintained (learning) in order not to degrade over time.

In this direction, a new generation of intelligent technology that incorporates multiple semi-autonomous knowledge-based systems and conventional techniques, representing distinct areas of expertise has emerged during the last years. These intelligent integrated systems (also called hybrid systems, Cooperating Expert Systems – CES - or distributed diagnosis systems) have been developed as a part of the Distributed Artificial Intelligence (DAI) research area. DAI technology concerns with the study and construction of automated systems that support co-ordinated intelligent behaviour in a group of semi-autonomous computational elements, called agents[2], to solve complex problems that individually would be solved with more difficulty. When facing a problem that could be solved effectively through cooperation from different perspectives, these agents solve this problem concurrently and integrating their results [Avouris and Page, 1995]. Some of the factors that strongly contributed to the emergence of this new Distributed AI field are: powerful concurrent computers, the widespread and generalisation of data networks, and the results of sociological studies that revealed the inherent task decomposition as well as the cooperative interactions that occur within human teams during problem solving activities [Malheiro and Oliveira, 1995]. Traditional areas of CES techniques have been speech and language processing, manufacturing and robotics, air traffic control, distributed sensing and interpretation, industrial monitoring and control. However, as the power of distributed processing systems increases and more advanced cooperative algorithms and languages emerge, we observe spreading of these techniques towards new complex application areas, like environmental management.

Recent active research on intelligent control systems envisages an organised strategy that combines various modelling methods and utilises them efficiently. A reasonable distributed proposal outlines the scope for the integration of tools from AI (pattern recognition, knowledge-based systems, fuzzy logic, neural networks, or inductive decision trees), which handle the particular characteristics of complex processes (*e.g.*, environmental

[2] By agents, we mean independent stand-alone computational processes that are committed to problem solving in a specific domain.

problems), with numerical and conventional computational techniques (statistical methods, advanced and robust control algorithms and system identification techniques). According to [Stephanopoulos and Han, 1996] conclusions, to provide engineering tools that solve mission-critical problems, one needs to develop a framework that allows to integrate an array of specific intelligent systems and numerical computations, allocating the detailed engineering to numerical computations (simulation, control, design, optimisation), while delegating the logical analysis and reasoning to supervisory intelligent systems. The inclusion of AI systems into a distributed problem-solving architecture enables convenient integration of diverse forms of knowledge (diversity and complementarities of the problem solving methodologies), efficient and faster management, processing of the whole knowledge and data by means of parallel execution, modularity and extendibility, controls the complexity of AI systems and increases the powerful of the resulting system. When, for example, data necessary for applying expert systems are unavailable, incomplete or erroneous, another *intelligent* module comes in support. This characteristic of reducing the uncertainty of the problem by applying alternative reasoning techniques or knowledge bases, is a typical use of DAI approaches. It simulates the problem-solving behaviour of a group of experts who apply various problem solving methodologies and expertise in relation to a given formulated problem.

1.7.2.1 Differences Between KBS and DSS

These intelligent integrated systems are usually referred also as Knowledge-Based or Intelligent Decision Support Systems (KB-DSS). A Knowledge Based-Decision Support System is a computer information system that provides information and methodological knowledge (domain knowledge and decision methodology knowledge) by means of analytical decision models (system and users), and access to databases and knowledge bases to support a decision maker in making decisions effectively in complex and ill-structured tasks. The KB-DSS are multi-layered information systems that reduce the time in which decisions can be made as well as the consistency and the quality of the decisions by offering criteria for the evaluation of alternatives or for justifying decisions. Thus, in contrast to a traditional decision support system (DSS) that only supports the decision process, a KB-DSS is able to take the decision itself. In particular, DSS developed to be used in environmental domains are referred as Environmental Decision Support Systems (EDSS, to be strict: Knowledge-Based Environmental Decision Support Systems, KB-EDSS) [Cortés *et al.*, 1999]. Sometimes they are also referred as integrated environmental information systems [Guariso and Page, 1994].

A traditional DSS is a computer program that provides information in a given domain of application by means of analytical decision models and access to databases, in order to support decision maker to make effective decisions about complex and ill-structured tasks. A DSS is composed of three components: A database and its management, a model base and its management, and a human-machine interface. Common DSS focus on quantitative mathematical and computational reasoning. DSS are a branch of operations research (OR) that evolved from the need to apply quantitative techniques to the solution of complex management problems [Darlington, 2000]. DSS are traditionally defined as the application of OR and computing (data processing) to support the management decision process. Knowledge-Based Systems, in contrast, can make decisions themselves. In practice, however, they would often be used for advisory purpose, that is, with the user retaining control, authority and responsibility, and only consulting the system for advice or confirmation. Other differences:

- KBS solutions are not applied to problems that require mathematical optimisation techniques
- KBS can be applied to problems where objective and constraints are difficult to specify in quantitative terms
- KBS are effective for eliciting alternatives as part of the solution process, due to the reasoning capabilities of KBS

A DSS typically gives full control to the decision maker about information acquisition, information analysis (quantitatively) and the final decision. A KBS, on the other hand, is free from acquisition, evaluation and judgmental biases (if the knowledge of the expert is properly represented in the ES and if the ES is properly designed). The ES can provide intelligence and make a tentative decision.

1.7.2.2 Features of Intelligent Integrated Systems

Some of the features and tasks that these intelligent integrated systems must be able to carry out include [Rizzoli and Young, 1997]: a) ability to acquire, represent and structure the knowledge in the domain under study; b) allow the separation of data and knowledge from models; c) ability to be used effectively for diagnosis, management and control. The latter includes [Stephanopoulos and Han, 1996]: (i) ability to distinguish between normal and abnormal operating conditions; (ii) identification of the causes of abnormal operating condition (*e.g.*, external load disturbances, equipment faults, operational degradation, operator-induced mishandling); (iii) capacity to evaluate current process trends and anticipate future operational states; and (iv), ability to create action plans and to schedule sequences of operating steps to bring the plant at the desired operating level.

1.7.2.3 Implementation of Intelligent Integrated Systems

The development of the intelligent integrated system needs: (a) a modelling language, for the description of all elements, *e.g.*, flow sheets, processing units, parameters, variables, relationships, rules, methods…and (b) a set of decision-making tools (selection of KBSs and other AI techniques) and numerical algorithms (controllers, simulators…) for the knowledge representation. These intelligent integrated approaches can be implemented in several architectures. The most widely used are:

- blackboard architecture where expertise is divided among sub domains and different reasoning techniques can be used in each sub domain. The blackboard is used, then, to integrate the various lines of reasoning,
- message passing or contract nets where messages are exchanged asynchronously among the different modules with no centralisation at all, agents are completely autonomous [Avouris and Page, 1995],
- Not Explicitly Coordinated Systems (NECS), which are formed of very complex autonomous agents and a centralised database, and,
- supervisory systems where a centralised control component plans all global activities

Object-based or object-oriented languages, where knowledge is maintained and extended through classes in class hierarchies, have been proposed as a powerful tool for building intelligent integrated systems.

The references [Cortés *et al*., 2000] and [Avouris, 1995] contain an extensive and updated survey of integrated intelligent decision support systems in environmental applications. They report: OASIS (for supporting a water management district), FRAME and DUSTRO (for air quality control), STORMCAST and MEDEX (for supporting storm and weather forecasting, respectively), LCPS (Low Clouds Prediction System), MEXSES (rule-based expert system for environmental impact assessment), INFORMS-R8 (for forest management), PHOENIX (fire-fighting simulator for managing forest-fires), DCHEM (Distributed Chemical Emergency Manager), CHARADE (for environmental emergencies), DAI-DEPUR (for WWTP operation), [Quah *et al*., 1996] (for different environmental situations) and [Rao *et al*., 1998], [Stylios and Groumpos, 1999] and [Özyurt *et al*., 1998] (for process industry systems).

1.7.2.4 Application to Wastewater Treatment Plants

A deep approach is also still necessary to obtain an optimal WWTP management because the use of the individual KBS cited above solves only certain aspects of the overall WWTP management process. Thus, the application of these hybrid approaches to the supervision of wastewater treatment systems may provide a typical case study of environmental problem that can effectively show their advantages. The hybrid systems look for integrating different diagnostic techniques which handle these particular characteristics (knowledge-based systems) with the mathematical or numerical computations (*e.g.* of a model or a traditional DSS) to optimise the management of a real WWTP by means of an upper level supervision. The multidisciplinary supervision and control of activated sludge processes must include: monitoring (sensor development, continuous analysis equipment), modelling (equations that model the bioreactors behaviour), control (maintenance of good effluent quality and reduction of operating costs), qualitative information (microbiological information, water colour and odour, water appearance…), expert knowledge (supplied by the experience from plant managers and operators and literature reviews), and experiential knowledge (specific knowledge acquired from solving previous problems in the plant). This integrative approach will allow to reach the goal of having a plant integrated control, considering the interaction between automatic control and expert systems and to provide improvement in operating quality and economy, as well as providing stability and reliability in plants (*e.g.*, as personnel turnover occurs or in nights or weekends in the small plants when there is no personnel).

Some examples of integrated intelligent systems applied to wastewater treatment plants can already be found on literature ([Avouris and Page, 1995], [Sànchez-Marrè *et al*., 1996], [Rao *et al*., 1998], [Ohtsuki *et al*., 1998] and [Ashraf Islam *et al*., 1999]).

2 ANTECEDENTS

This chapter seeks to be a short resume of the work carried out by a multidisciplinary working group along the last ten years in the study, development and application of several techniques in the control and supervision of WWTP optimisation.

The results of cooperative research between the Environmental and Chemical Engineering Laboratory of the *Universitat de Girona* in close association with the Chemical Engineering Department of the *Universitat Autònoma de Barcelona* (UAB) and the Knowledge Engineering and Machine Learning Group (KEML) at the Software Department of the *Universitat Politècnica de Catalunya* (UPC) represent the previous work to this thesis.

Though this research group began with a classical approach, *e.g.* statistical modelling or feedback control, soon they realised that classical control techniques show some limitations and that more powerful strategies were necessary to deal with such complex environmental processes as WWTP. The special characteristics of these processes made this research group to think in the application of other techniques based on knowledge (knowledge-bases systems), which had initially been developed in other science fields like Artificial Intelligence, as a new proper step in the WWTP management and control. The research group began with standard expert systems, and soon evolved to the integration of Case-based Reasoning module to consider learning process with new experiences. In spite of KBS supposes a significant improvement, the application of a single knowledge-based technique also present some pitfalls since only enables to overcome some of the limitations of classical control techniques. The cooperative group became conscious that complex problems should be better addressed from a multidisciplinary way, integrating different techniques from artificial intelligence and conventional methods to solve the operational problems precisely. Indeed, as a result of the experience obtained thanks to several years of cooperative research, they have developed and intelligent integrated supervisory system to manage optimally complex wastewater treatment systems. This previous work and publications resulted are next briefly detailed.

Summarising, the following work (which is the previous work to this thesis) have arose from the close collaboration of these different research groups:

- advances in the modelling, control and simulation of the wastewater treatment process
- advances in analytical determinations and development of new on-line analysers
- advances in the understanding of the microorganisms and the biological processes involved in the BNR process
- application of some Artificial Intelligence techniques to support the control and supervision of WWTP
- development of an intelligent integrated system to supervise WWTP: DAI-DEPUR

2.1 Classical Approach

Their first approach to the improvement of the WWTP management was a classical approach, applying their research background in modelling other environmental processes (river quality and lab bioreactors, [Poch, 1990]). Numerical modelling, parameter estimation techniques for fault detection, and recursive techniques are some clear examples to define our first approach to the domain of WWTP.

Initially, the group focused their efforts in the development of numerical models to implement in control algorithms in order to improve WWTP control. The relationships between the different state variables (different kinds of substrates and microorganisms) were established ([Robusté *et al.*, 1988] and [Robusté and Poch, 1988]). An adaptative control algorithm for maintaining the desired DO level in the bioreactor was presented in [Serra *et al.*, 1993]. Later, this research group acquired a General Purpose Simulator specific for wastewater treatment plants, the GPS-X simulator [Hydromantis, 1995], which includes all the models developed by the IWA specialised modelling group and some modifications of those. Another important part of this work was centred in combining activated sludge models with mathematical identification techniques to model the behaviour of the state variables that characterise the process and cannot be measured directly on-line (substrate and biomass concentration). The combination of modelling and identification allows the plant manager to evaluate in advance the effect that different actions could cause over the plant. This can be done by means of two methodologies:

- automatically through non-linear predictive control algorithms were the organic matter is modelled with identifying recursive techniques of OUR ([Moreno *et al.*, 1992] and [De Prada *et al.*, 1991])
- an interactive methodology where the plant manager proposes an action and the system advice about the answer of the system according to the previously calibrated model

Parameter estimation techniques enabled also fault detection in a real wastewater [Fuente *et al.*, 1996].

The main advantage of using models and/or simulation are that enable to evaluate WWTP behaviour in front of certain scenarios with different operational conditions and influent composition and that can help to predict, at medium and long-term, the possible consequences of alternative actions applied over the process. The use of models and/or simulations also facilitates the WWTP control since enables decision maker to carry out several studies more: to calibrate[3] kinetic and stoichiometric parameters of the IWA mechanistic models for a specific plant, to carry out sensitivity analysis of any kinetic or operational parameter within the model, and to study different alternatives for upgrading or retrofitting existing WWTP from organic to nutrient removal ([Colprim, 1998] and [Colprim *et al.*, 1999]). In spite of those advantages, soon the scientific community realised that the use of numerical models present some limitations that difficult their application:

[3] For the calibration of the involved kinetic parameters of a model to simulate the experiments carried out in a pilot plant, the authors have also used an optimisation algorithm (Serra, 1992, Albiol, 1993).

- the results of simulation from mechanistic models are only valid when applied appropriately, *i.e.* when describing plant behaviour in situations that have been considered during the calibration phase. They cannot deal with unforeseen situations.
- abnormal episodes involving symbolic variables (for example, filamentous bacteria proliferation, protozoan predominant, water colour or the presence of bubbles in the V30-settling test) cannot be easily modelled because classical models cannot deal with qualitative features, which are essential for this problem identification and solving (bulking, rising…). For example, in [Van Niekerk *et al*., 1987], bulking was not satisfactorily modelled.
- the models are not easy to develop, often are inaccurate and overly simplistic representations of reality.
- the plant never works under steady state conditions, instead, its operational conditions are continuously changing. As a difference to most industrial processes where type and quantity of raw material are controlled, the WWTP receive a wastewater flow rate and pollutant concentrations that are absolutely variable and uncontrollable.
- the presence and interrelation of thousands of species of microorganisms difficult the establishment of a valid mechanism to describe the behaviour of the system (*ill-structured domain*).
- the input data is full of missing data because much of the WWTPs do not analyse all the parameters every day.
- the large number of parameters involved makes them not useful to control the dynamic process on-line (short-term control). Moreover, most of the numerical variables cannot be obtained on-line; on the contrary, some of them have important analytic delays (from hours to days for the BOD).
- important maintenance effort for the reliable functioning of on-line analysers (ammonia, nitrite, nitrate, dissolved oxygen).

2.2 Instrumentation

In any case, the development of optimal control algorithms (based on both mechanistic or black-box models) requires the use of reliable on-line analysers of nitrogen and phosphorous compounds. Many years ago, there were few of them and they were very expensive, so this research group began a research line in order to improve the existing on-line analysers and to develop new and more reliable sensors to be applied to bio-processes for on-line determination of COD, ammonia, nitrite nitrate and phosphate. an automated COD determination with a redox electrode ([García-Raurich *et al*., 1993]) and a method based on microwave digestion ([del Valle *et al*., 1990]).

In this sense, an analyser of the nitrogen cycle compounds contained based in the Flow Injection Analysis (FIA) technique was successfully developed ([Gabriel *et al*., 1998]). Also successful results were obtained in the modelling and optimisation of these flow injection systems. Both mechanistic [de Gràcia *et al*., 1993] as well as neural networks ([Campmajó *et al*., 1992]) modelled satisfactorily the results of FIA. Poch *et al.* proposed a new methodology for the optimisation of FIAs [Poch *et al.,* 1993]. With respect to microbiological information, advanced techniques of molecular analysis are needed to identify the mic roorganisms responsible for nitrification, their oxidising activity and to study the effect of operational conditions and toxicants on them [Amer *et al*., 1998].

In spite of the tangible advances in instrumentation, this cooperative research group realised that classical control methods, based on mathematical modelling, could not overcome all their limitations when controlling the activated sludge process of real WWTP.

2.3 Intelligent Systems

In order to get a significant progress in wastewater treatment control and supervision when facing abnormal situations and, bearing in mind the main advantages and characteristics of intelligent systems, this research group began to work with these systems, mainly knowledge-based systems.

The original idea and some previous results were presented in [Serra *et al*., 1993], [Serra *et al*., 1994] and [Serra *et al*., 1997]. The first approach of application of knowledge-based systems to the WWTP domain was the development of DEPUR [Serra *et al*., 1994], an off-line expert system[4] tool or rule-based system for the diagnosis step using simple decision trees and inference rules obtained from an unsupervised classification tool called Linneo+ ([Sànchez-Marrè *et al*., 1997b], [Béjar *et al*., 1997] and [Béjar, 1995]). These results and the interaction with the plant manager enable to built the first prototype of an expert system to diagnose some (six) operational problems in the Manresa WWTP. The evolution of this off-line Expert System was a knowledge-based system called Intelligent System for Supervision and Control of WAstewater treatment Plants ([Serra *et al.,* 1997]). This system is capable to handle with several usual situations (where mathematical control can be useful) and also with some abnormal situations (where quantitative and qualitative information must be considered). Therefore, it is the first time that numerical control and knowledge-based systems show some cooperation although they are not integrated in a real DAI architecture yet. The use of ES allowed to overcome the limitations of classical control but, at the same time, we experienced significant drawbacks when applying this technique to the WWTP supervision. Among the main disadvantages, there were: (1) most of the acquired knowledge is general knowledge to manage any WWTP (coming from literature revision). There is a lack of specificity, mainly in the repertory actions proposed, (2) the bottleneck of knowledge acquisition and maybe, the most important, (3) the knowledge base is static.

These limitations hinder the use of ES as the sole control system for complex processes and make the group to think in to apply another technique to complement and overcome these drawbacks. The group pointed to the

[4] An expert system is a computer programs that can mimic many human decision-making processes (heuristic) to deal with a specific problem. An ES is composed of the knowledge base (KB) and an inference engine. For the implementation of the expert system it was necessary to built the knowledge base of the process (KB), codified as inference rules, through the knowledge acquisition process. This knowledge acquisition can be made classically, it means through literature review and the establishment of a set of interviews with the experts of the process, or with the help of some AI techniques.

incorporation of Case-based reasoning as the most suitable technique to fulfil those requirements: use of specific knowledge of the own facility and learning capabilities. A case-based system was designed to re-use experiential knowledge via case-based reasoning and learning to collaborate with the previous expert system [Sànchez-Marrè *et al.*, 1997a]. The disadvantage is that the case-based system will not be able to confront a totally new situation never lived by the plant. In this case, what is important is to register this new case, the action applied, and the evaluation and to store it in the case-library (learning process). The final objective is that the system learns automatically.

The group has also explored the field of soft computing techniques, in particular, by experimenting with neural networks and fuzzy approaches. The final aim is to develop non-mechanistic or black-box models, where one do not care about the internal processes involved but about the inputs and outputs of the process. These kinds of models have been proved to perform well when predicting the evolution of the activated sludge processes in short-term. Specifically, system identification and real-time pattern recognition by neural networks were studied to estimate key parameters (*e.g.* COD in the outflow) in the activated sludge process ([Fu and Poch, 1993], [Fu and Poch, 1995a], [Fu and Poch, 1995b] and [Fu and Poch, 1998]). In a still current research, heterogeneous time-delay neural networks have been experimented to study the influence of qualitative variables coming from microscopic examinations and subjective remarks of the operators, in the prediction of the sludge settleability. This model, in which inputs are a mixture of continuous (crisp, rough or fuzzy) and discrete values, performs effectively even when dealing with missing values ([Belanche *et al.*, 1999b] and [Belanche *et al.*, 2000]). Anyway, the main disadvantage of neural networks is peculiarly related with its main advantage: no knowledge is required to be elicitated from experts. This fact accelerates its development but also makes not possible for the expert to introduce knowledge and to find an explanation of the results, because the connection weights of the networks do not have obvious interpretations.

2.4 Intelligent Integration

During the last years, most of the research efforts in artificial intelligence have been focused in solving the problems of conventional processes by applying one of different approaches of the KBS. Specially related to the wastewater treatment, KBS techniques have been developed as off-line consultations for: diagnosis, design, process optimisation…But all these approaches solve only certain aspects of the overall WWTP management process and have one the KBS problems already mentioned. Thus, it seems that the management of the whole WWTP (system evaluation, diagnosis, supervision, action) could be more easily achieved within an architecture that integrates and complements these different problem solving elements and make the overall system more powerful due to the synergic effects.

As a clear conclusion of the whole work carried out, the group suggested the integration of different AI and classical tools in a multidisciplinary approach as the most optimal solution to guaranty the successful control of complex processes like WWTP. This integration must be done on a suitable architecture, which is able to distribute and supervise the different tasks of the system, and to deal with the different kind of data and knowledge considered. Specifically, this DAI architecture efficiently manage and integrate two different types of knowledge representation (**expert systems**, which mainly incorporates the general expert knowledge acquired by the scientific experience existing over the process, and **case-based system**, including the specific experiential knowledge acquired through practical experiences of a particular system) with the automatic control algorithms to control and supervise the activated sludge process (from now on, we will mainly refer to the EDSS as a Supervisory System). The theoretical basis of the this distributed and multi-level architecture (*the DAI-DEPUR architecture*), integrating an expert system, case-base reasoning and the numerical control module, are presented in [Sànchez-Marrè *et al.*, 1996], while the protocol that must be followed to build the whole Supervisory System for any WWTP was proposed in [R-Roda, 1998].

Development of a protocol for the implementation of the Supervisory System to any WWTP

The *off-line* application of these techniques to different Catalan WWTP (*Manresa*, *Cassà de la Selva*, *Girona*, *Lloret de Mar*) enabled to check their functionality to deal with heterogeneous (quantitative and qualitative) and missing data and to carry out problem-solving tasks ([R-Roda, 1998] and [Comas *et al.*, 1997]). This experimentation phase provides the group of large and satisfactory experience, which encouraged them to develop a protocol to be followed when trying to integrate Knowledge Based techniques and numerical control to WWTP control and supervision ([R.-Roda *et al.*, 1999a], [R.-Roda *et al.*, 1999c] and [R.-Roda, 1998]). A list of main points of the protocol is detailed here: previous study of the plant, deep literature search, interviews with the operators, study of the database of the plant, Expert System development, Case-Based Reasoning System development, integration, validation, application and final evaluation of the prototype.

Simultaneously, some modifications and adjustments on the algorithms implemented in the CBS were made whilst others were new developed (case retrieving algorithm, learning algorithm, similarity algorithm) allowing the overall performance improvement. The most relevant results can be found on these references: [Sànchez-Marrè *et al.*, 1998], [Sànchez-Marrè *et al.*, 1999a], and [Sànchez-Marrè *et al.*, 2000].

Development and real implementation of the Supervisory System for a Pilot Plant

Lately, the DAI architecture was generalised to tackle with biological nutrient removal and validated in a pilot plant [Baeza, 1999]. This pilot plant was constructed and performed continuously during 5 years with the typical configuration of BNR in order to study the best possible policies to apply to the Manresa WWTP to upgrade it to biological nitrogen removal. The pilot plant is connected to a computer governing the analysers and PLCs, which is connected to the workstation with the Supervisory System. Simultaneously, the workstation is connected to Internet, allowing to be governed or their data to be accessed from any computer connected to Internet. The Supervisory System realised very satisfactory since levels lower than 15 mg/l of total nitrogen were attained during the whole experimental phase ([Baeza *et al.*, 2000]).

Development and real implementation of the Supervisory System for a large WWTP (Granollers)

All this previous work made during last ten years really supposed a great advance in the improvement of wastewater treatment plant control and supervision. Nevertheless, this research group still had the sensation of a lack of an overall implementation in a real plant. At that moment, the group had obtained pleasing results when applying these techniques off-line and separately to diverse real plants and together, as a Supervisory System, only in a pilot plant. The group wanted to implement the overall Supervisory System in a real plant working in real time and see how it evolves confronting real operational problems. Thus, the implementation and validation of the whole system in a real WWTP culminates the efforts of theoretical and partial practical efforts (design and development of automatic control algorithms, expert system, case-based system...) carried out by this cooperative research group during several years.

On the other hand, the local administration responsible of water quality of the basin of river Besòs (*Consorci per la Defensa de la Conca del Riu Besòs,* CDCRB) was interested in the study and optimisation of the wastewater treatment systems management by means of the implementation of some advanced approach. They wanted to improve the WWTP operation and control by assisting plant managers and operators in their decision making process when solving problems. They were looking for more efficient techniques to increase the WWTP reliability and decrease the energetic costs, while maintaining the effluent quality criteria. This reciprocal interest between Academia and the CDCRB motivated the concern to develop the intelligent supervisory system following the protocol suggested in [R.-Roda, 1998] to the Granollers WWTP. The choice of the Granollers WWTP was made taking into account some special characteristics that increase the potential advantages of applying this Supervisory System (see chapter 4). This real implementation will make possible to show the potential possibilities of this system to the experts of the process and will enable to definitively demonstrate the feasible applicability to improve the WWTP management. Hence, the development (expert and case-based system will be updated and upgraded), implementation and evaluation of the Supervisory System to a real WWTP are the main scope of the present thesis. The evaluation of the system gives first attention to the individual validation of each technique and then, to the field validation of the overall architecture as a real time Supervisory System for WWTP operation and control. The *feedback* obtained from this real application will be very important in order to discover the weak points, refine the intelligent supervisory system and prepare the portability of the system to any plant in both short time and cost.

3 OBJECTIVES

The main objective of the present thesis is to test the feasibility of a Supervisory System to improve the management of a real WWTP. It involves the development, implementation and evaluation of the Supervisory System and enables to establish the following *sub*-objectives:

- Review of the work carried out by our research group identifying the existing gaps
- Expert System development: this task involves the knowledge acquisition to build the KB and the codification of the Expert System. The knowledge acquisition process includes general knowledge acquisition (extensive literature review, expert interviews) and specific knowledge acquisition (expert interviews and application of machine learning techniques to database).
- Case-Based System development: definition of the case, case-library and selection of the initial seed.
- Integration of the knowledge-based systems, simulation models and conventional techniques within the general integrated structure of the Supervisory System.
- Partial validation of each module of the Supervisory System
- Implementation of this intelligent integrated supervisory system to a real WWTP
- Evaluation of the intelligent integrated supervisory system as a suitable support tool to improve the management of a real WWTP. Validation with real problems of the plant (*field validation*).

4 EXPERIMENTAL SYSTEM

4.1 Plant description

4.1.1 Objective

The wastewater treatment plant selected to develop and apply our proposed Supervisory System prototype is located in Granollers, in the Besòs river basin (Catalonia, NE of Spain). This plant initially included preliminary and physical-chemical treatment for organic matter and suspended solids removal (built in 1992). In April 1998, the plant was extended to biological treatment and physical-chemical treatment was completely replaced. Later on, the plant was retrofitted to the actual Ludzack-Ettinger configuration. Therefore, nowadays, this facility provides preliminary, primary and secondary treatment to remove the organic matter, suspended solids and, under some conditions, nitrogen contained in the raw water of about 130,000 inhabitant-equivalents. The raw influent comes from a sewer that collects the urban and industrial wastewater together. A current plan of the Granollers WWTP is shown in Picture 1.

Picture 1 Aerial picture of the Granollers WWTP

4.1.2 Current plant configuration

The overall treatment process of wastewater in the Granollers WWTP, as in any other plant, can be divided into two main treatment lines: water and sludge. Three phases can be distinguished in the water treatment line: preliminary treatment, primary treatment, and secondary (biological) treatment. The configuration of the secondary treatment is based on either the conventional Ludzack-Ettinger or the modified Ludzack-Ettinger, depending on whether or not there is a removal of nitrogen in the plant. On the other hand, the treatment line for sludge encompasses the following steps: thickening, anaerobic digestion, dewatering and final disposal into a controlled landfill. A flow sheet of the water and sludge line (except anaerobic digesters and dewatering units) of the Granollers WWTP is presented in Figure 6.

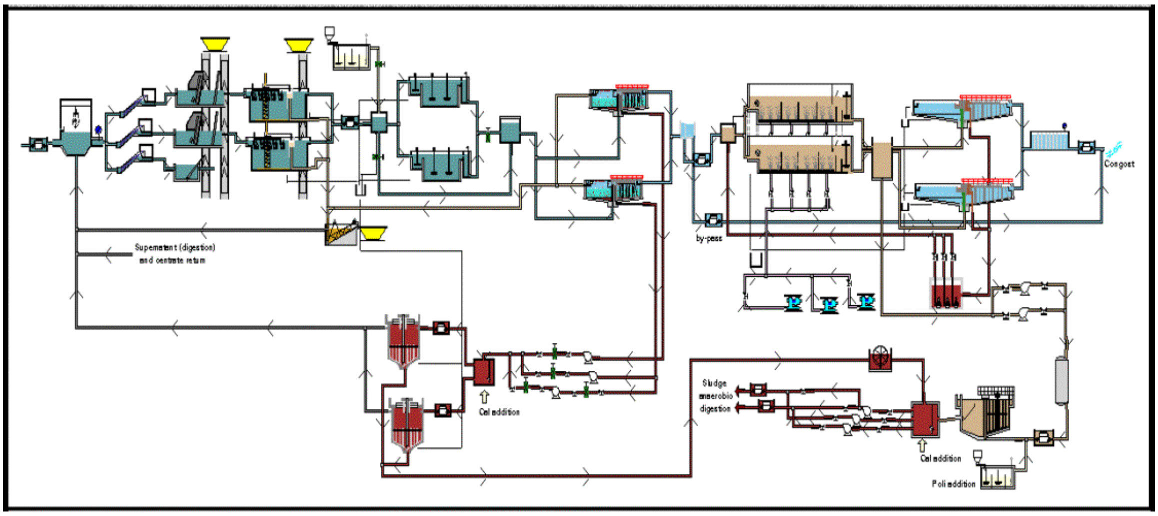

Figure 6 Flow sheet of the WWTP water line

The **preliminary treatment** includes screening for coarse particles removal (manual bar racks) and grit and floatable removal (with one mechanically cleaned bar screen). Wastewater is then impelled to the primary and secondary treatment units by means of three Archimedes screws (each one gives 1200 m^3/h). The plant usually operates with one Archimedes, but the second one is switched on in daily peak flows periods to avoid overflowing. The maximum capacity of biological treatment is not reached when one Archimedes operates, but it can be exceeded when the two Archimedes are on. Therefore, during heavy storms is likely that part of the influent will be by-passed to avoid sludge losses from the biological reactor.

The **primary treatment** consists of two circular primary sedimentation tanks with a sludge-scraping mechanism for physical sedimentation of suspended solids (previously used as physical-chemical treatment). Physical-chemical treatment has been actually abandoned, except in case of heavy rain (when ferric chloride is dosed at 80 mg/l and polyelectrolyte is added as function of turbidity). Sometimes one of the primary settler tanks is utilised as flow equaliser (to avoid hydraulic shocks and loading oscillations) or pre-fermentation unit (for obtaining easily biodegradable organics for denitrification). Primary excess sludge is intermittently wasted according to the schedule implemented into the SCADA. Normally, it is pumped for short durations at frequent intervals (wasting flow rate = 18 m^3/h). The primary sludge is dewatered by means of two thickeners before mixing with the excess biological solids coming from the flotation unit.

From the primary treatment, all the wastewater is derived to the **secondary** (biological) **treatment**. Wastewater flow rate by-pass is fixed to a set point fixed around 1500 m^3/h. Flow rates exceeding this set point (*i.e.*, in rainy or storm episodes) by-pass the biological treatment. Therefore, influent flow rates ranging from 1500 m^3/h to 2400 m^3/h (maximum flow rate given by Archimedes) is only treated with primary treatment.

The outflow from primary treatment units is distributed into two parallel and symmetric lines of biological treatment. The biological treatment consists of the conventional suspended growth system called activated sludge (biological reactor and secondary settler). The two biological reactors of the Granollers WWTP consist of a small anoxic selector (400 m^3) located at the beginning of the aeration tank, and a compartmentalised plug-flow reactor (3664 m^3). Each plug-flow reactor is compartmentalised into 4 aerated tanks. Each biological line accepts a maximum flow rate of 1500 m^3/h during 10 minutes (wastewater exceeding 2400-2500 m^3 have to be treated with the physical-chemical process). Therefore, each biological reactor line is equivalent to one anoxic reactor and four Continuous Stirred Tank Reactors (CSTR) with Ludzack-Ettinger configuration. When the N/D process is desired, anoxic conditions are also maintained in the first CSTR compartment of each line. A complete dissolved oxygen control enables to minimise the required air supplied. Each compartment has a dissolved oxygen sensor and its control loop is based on a PI controller. At the exit of both biological lines, the activated sludge is collected together again in a small de-aeration tank (10 m^3) from which the wasting of excess activated sludge is done. The wasting activated sludge from this point results in a desired small solids concentration because of the thickening of activated sludge is carried out with a flotation unit. From the de-aeration tank, the activated sludge is sent to the clarifier units. Each circular secondary sedimentation tank has 707 m^2 of surface.

The excess sludge wasting system includes two automatic pumps plus one of manual regulation (each one impels 65 m^3/h at the maximum velocity). The automatic sludge pumping is controlled by a PLC. The pumps for each tank operate at preset times with a pre-fixed frequency and duration. Wasting rates are limited by the sludge loading that is admitted by the flotation unit (7 kg $MS/m^2 \cdot d$). There is no problem when only one wasting pump functions but the flotation unit present hydraulic problems when the two sludge wasting pumps work together.

There are three recycle pumps available to recycle activated sludge settled in the clarifier to the aeration tank. Two recycle pumps functioning together give a flow rate similar to the mean inflow rate. In case of filamentous organisms proliferation, a chlorine tank is available to control them in the recycle activated sludge point (e.g., *Nocardia* problems are solved with anoxic zones and chlorination).

The fraction of the secondary effluent that is re-utilised by the WWTP services must be treated with ultraviolet rays. The plant is also equipped with possible effluent chlorination to be used in case of epidemics.

The **Sludge treatment** follows always the same process. After the flotation unit, the wasted activated sludge is mixed with the primary excess sludge coming from a thickener in a mixing tank. The total sludge load is then sent to the anaerobic digestion unit. The Granollers WWTP is equipped with two anaerobic digesters of 23 m. of diameter and 5000 m^3 of usable volume. After the stabilisation of the sludge with ferric chloride and lime, it is dewatered and dried. This process is conducted by means of 3 centrifuges. Side-streams from the centrifuges are mixed with the influent raw wastewater whilst the other "inside streams" are mixed with the biologic secondary influent. Finally, the dried sludge is disposed in a controlled landfill.

4.1.3 Special characteristics of Granollers WWTP

Granollers WWTP has several particular characteristics that increase the potential advantages of the development and application of an intelligent supervisory system to control and supervise the wastewater treatment process. Among these characteristics, we emphasise the following ones:

- Availability of a significant amount of historical records corresponding to the characterisation of the plant operation for over more than one year, These records include either quantitative information (*e.g.*, analytic determinations of sludge and water quality at different locations in the plant, and on-line signals from different sensors) and qualitative (*e.g.*, microscopic observations of mixed liquor twice or three times a week, biological foam presence, filamentous bulking sludge which interfere the settleability, sludge floating in clarifiers and, in general, any abnormal observation). The examination of these data enables the acquisition of specific and objective knowledge, necessary to ensure the sound development of our Supervisory System.
- This plant has a great level of automation centralised in a computer that collects on-line data and controls most of the plant operations.
- The Granollers WWTP is a system with a high variability. A continuous change in the hourly loading is experienced because the plant is located in an area of the Besòs river basin with an important contribution of industrial activities. For example, in summer when the industries stop their activities, the biologic reactor works much better and is more stable.
- Existence of a broad array of different situations that take place throughout the year (storms, overloading, nitrification in hot periods, uncontrolled industrial spills…), causing significant changes in the influent characteristics, which affect the standard process operation.
- A certain degree of flexibility in the plant configuration that enables a partial nitrification/denitrification in warm periods, using the primary settlers as flow equalisers or pre-fermentation units. This fact gives a broad array of possibilities to act over the process.
- High level of specialisation of plant experts who have been working in the plant from the beginning of its operation. They know perfectly all type of details that constitute the heuristic knowledge of the plant.
- The Supervisory System will result in an historical memory of the process and will help the plant manager. Whenever the operating company is changed (and also plant manager), the Supervisory System would be an inestimable aid for the new incoming one.

4.1.4 Wastewater Characterisation

Typical concentrations in the Granollers WWTP inflow are listed in Table 2. These values were obtained from the statistical analysis of the historical data recorded during the period from April 1st, 1998 to April 4th, 2000 (twenty-five months of operation).

Parameter at influent	Mean	Standard deviation	Min	Max	Missing
Inflow rate	22142	7323	100	59400	61
pH	8.1	1.2	7.3	9.1	63
COD (mg O_2/l)	766	191	229	2850	3
BOD (mg O_2/l)	420	111	140	1000	23
SS (mg TSS/l)	292	109	88	1640	3
TKN (mg N/l)	115	43	64	285	286
NH_4^+ (mg N/l)	75	30	42	230	283
Conductivity (µS/cm)	5753	1365	1000	9060	54
Total-P (mg P-PO_4^{3-}/l)	14.3	4.1	6.6	19.3	290
Turbidity (NTU)	179	57	98	726	214

Table 2 Basic statistical descriptors for influent characteristics

Wastewater flow rates vary within days, weeks and even among seasons. Daily (diurnal) flows for Granollers WWTPs peak between 8 and 10 a.m., between 11 a.m. and 13 p.m., between 14:30 and 16:30 p.m. and between 21 and 23 p.m., approximately (see Figure 7). The daily peak flow exceeds the daily average flow by 40 to 170% (in extreme cases). Minimum flows typically occur early in the morning. The mean inflow rate represents a hydraulic retention time in the plant of about 6-7 hours.

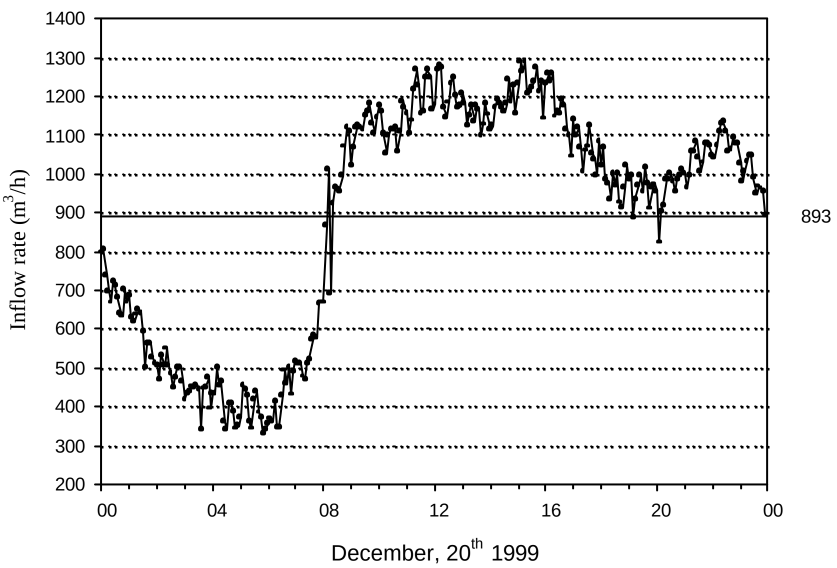

Figure 7 Typical daily profile of influent flow rate (labour day)

Significant weekly variation can be observed between labour days and weekends due to the habits of people and the important contribution of industrial effluents to the influent wastewater of Granollers. Figure 8 shows the typical profile of the inflow rate over a week.

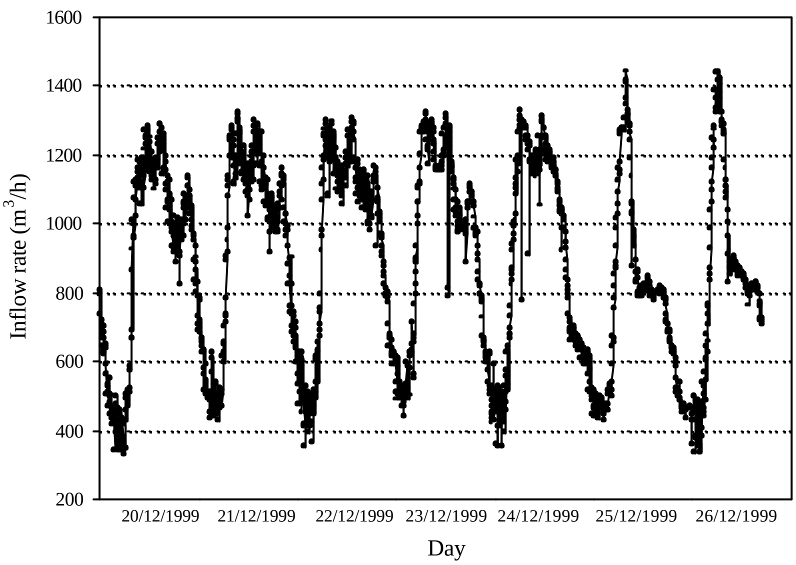

Figure 8 Influent profile throughout a week

4.1.5 Operation and control

The control of the activated sludge process consists of selecting the proper operational parameters that provide the best performance at the least cost using the present and historical operating data as well as laboratory test results. These operational parameters include: F:M ratio, SRT, MLSS concentration, Mixed Liquor Volatile Suspended Solids (MLVSS) concentration, MLSS/effluent quality ratio, DO level, Sludge Volume Index (SVI), microscopic examination, and the quality of the removed solids. These parameters allow the control of aeration, Recycle Activated Sludge (RAS) and Waste Activated Sludge (WAS) rates, and chemical feed rates (chlorine, settling aids, and nutrients) if required. To control nitrification, additional parameters are considered. These are: TKN loading, BOD:TKN ratio, and pH to avoid low alkalinity problems. Activated sludge process is operated to control the effluent nitrogen and organic matter according to the required standards based on the actual legislation.

When the WWTP removal efficiencies do not meet the desired effluent quality, the plant manager must take some action to counteract the causes of this lower efficiency. In the Granollers WWTP, the control actions addressed to solve any abnormal situation are based on next aspects:

1- the excess of biological sludge is wasted automatically according to the scheduled operation time of suction pumps which is fixed as a function of the desired F:M ratio,

2- automatic control of the biological aeration: PI controllers automatically regulate oxygen supplied as a function of the established set points,

3- variations of the activated sludge recycle depending on the secondary inflow rate and MLSS concentration,

4- flow equalisation to avoid large oscillations in the settling velocity

5- by-pass of part of the inflow rate in case of a very high hydraulic loading (regulation of the amount of wastewater to be treated) or by-pass of the biological treatment as a function of a previously established set point

6- dosage of chemicals to improve sedimentation, to add nutrients or to control filamentous organism
7- variation of anoxic/aerobic time and volume
8- variation of internal recycle (or recirculation) flow rate

Up to now, the SCADA system existing in Granollers regulates most of these control actions by means of the PLCs network. A SCADA normally implements programmed procedures to automatically execute some actions. In particular, in Granollers, the SCADA *enables* realisation of the first four actions mentioned above, which will be now discussed in detail: wasting rate, oxygen, recycle control, and flow equalisation.

Control of Wasting Activated Sludge

The most important technique used to routinely control the activated sludge process is to control the solids inventory in the system with the wasting rate. The wasting of activated sludge (WAS) affects the process more than any other process control adjustment. WAS maintains a balance between the amount of microorganisms and the amount of food expressed as BOD or COD. In Granollers, the control of sludge wasted is done by the constant F:M ratio method. This method is based on fixing the wasted sludge rate to **maintain a constant F:M ratio**, which has been heuristically determined. Usually, a good operational state of WWTPs is mainly achieved when the balance between substrate and biomass (F:M) is guaranteed. This balance is very sensitive to the changes in the process operating conditions. This control method is used to ensure that the activated sludge process is being loaded at a rate that allows microorganisms in the MLSS to use most of the food supply in the wastewater being treated. The calculation is expressed as

$$\frac{F}{M} = \frac{\text{Influent BOD5 into the activated sludge process}}{\text{Volatile solids inventory within the aeration system}}\left[\frac{\text{kg BOD}}{\text{kg MLVSS}\cdot\text{d}}\right]$$

where, Influent BOD_5 into the activated sludge process = Inflow rate (m^3/d) x primary effluent BOD (g/m^3), and,
Volatile solids inventory within the aeration system = $V_{reactor}$ (m^3) x MLVSS (g/m^3)

The actual F:M ratio (calculated using a 7-day moving average) can be used to determine wasting rates by determining the desired MLVSS (and then the desired MLSS). Then, the desired MLSS can be used to calculate the wasting rate based on maintaining a constant F:M rate. Once the wasting rate is estimated, it can be scheduled throughout the SCADA, taking into account that two wasting pumps of a fixed velocity are available, so they can only be switched on or off. In normal situations, the plant works properly with F:M ratios around the design value (0.35 kg BOD/kg TSS·d).

The SRT is also a fundamental parameter used as an indicator of the biomass state and because that, of the treatment process. The F:M control method influences directly over the SRT value. If the plant performs perfectly, SRT is fixed taking into account only the wasted activated sludge. Actually, most of the plants (and, also Granollers) present activated sludge losses by the effluent and by the floatable removing mechanisms (*i.e.* skimmers), which must be considered in the SRT calculation. However, the SRT values in Granollers must always be higher than 4.7 days since it is limited by the capacity of the sludge suction pump (maximum flow rate of 65 m^3/h) and also by the flotation unit capacity.

Aeration control

The amount of oxygen that must be transferred to the biological tanks by the aeration system varies during the day because of the influent BOD and TKN loading daily variation. In the Granollers WWTP, the aeration system consists of a diffused air system, in which compressed air is introduced at the bottom of the aeration tank through a system producing fine air bubbles.

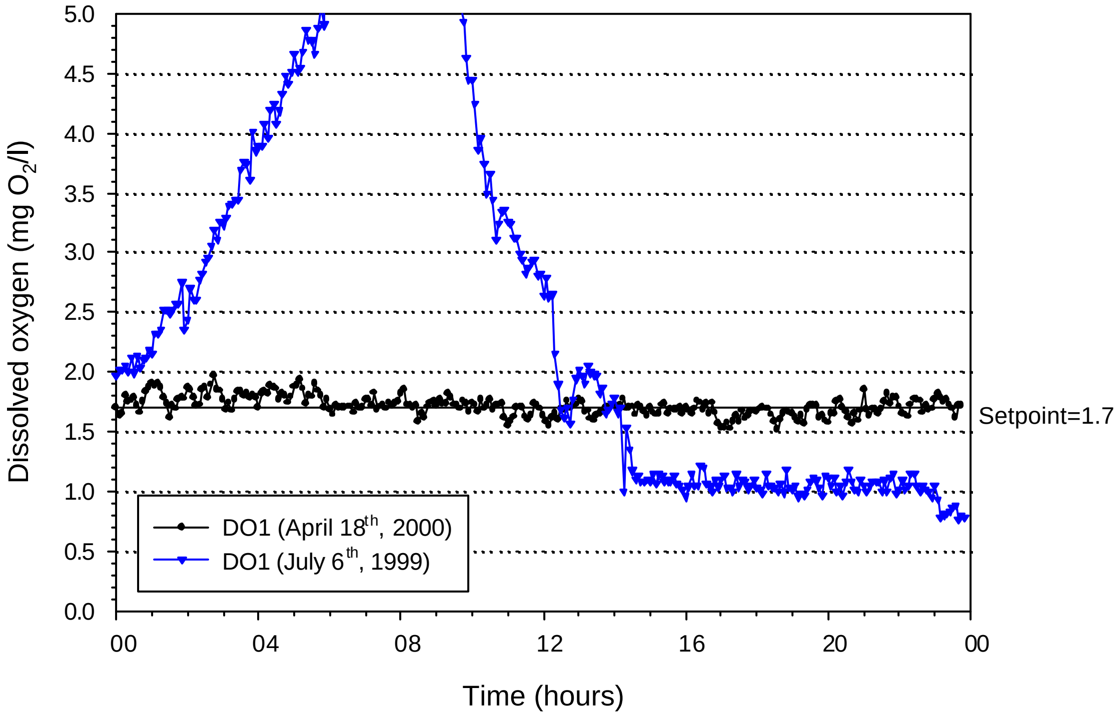

Figure 9 Dissolved oxygen level before and after the distributed DO control

The dissolved oxygen control system has also undergone an evolution. Initially, the air supplied to the whole aeration tank was regulated by means of a mathematical algorithm implemented in a classical PI controller, to maintain DO level at the last (fourth) compartment within preset set points. The DO controllers received the DO reading from the only DO probe installed in the last (fourth) compartment, but produced errors in the DO level at the first and second compartments (*i.e.*, shortage of DO during peak flows and excess of air during under loaded periods, see Figure 9). The DO control is a typical automatic control available at most of the WWTP.

From November 9th 1999, a distributed DO control system was implemented into the SCADA. Each one of the 8 compartments of both lines in the aeration tanks is independently controlled. With this change, there is a close control loop for each aerated compartment with its DO probe and therefore, a different set point could be established for each compartment. Set points are usually fixed around 2 or a little lower if nitrification is not desired (or cannot be accomplished due to low temperatures). The overall airflow supplied is calculated as the sum of the airflow required for each compartment. The control variable and the set point fixed are evaluated with a proportional-integral (PI) algorithm implemented into the SCADA. Figure shows the daily behaviour of the DO level in the compartment 1 before and after the implementation of this distributed control.

Control of the Recycle Activated Sludge

A part from the DO set points and the wasting rates scheduled throughout the SCADA, another control parameter that can be automatically modified is the recycle flow rate of activated sludge. The recycle of activated sludge (RAS) from the secondary clarifier to the aeration tank is also a key control parameter to properly operate the activated sludge process. The activated sludge should be recycled to achieve and maintain a good settling mixed liquor. In Granollers, the sludge is returned at a **varying** rate (as a function of the secondary influent flow rate and MLSS concentration which is normally around 3000 mg/l SS) to optimise the concentration and retention time of solids in the clarifier. The volume of activated sludge settled in 30 minutes (V30) can be used as a control parameter to estimate the optimal recycle rates.

If the plant works with only one recycle pump, the sludge settles efficiently but if nitrates are present, rising of sludge can happen. If two or three recycle pumps are functioning simultaneously, the hydraulic retention time in the clarifier is reduced and nitrates have not enough time to be denitrified, but upflow velocity (defined as secondary inflow rate/settling surface) increases a lot causing turbulences and losses of activated sludge floc through the effluent. Therefore, when the plant is nitrifying, recycle rate is modified according not only to inflow rate and MLSS, but also, to nitrate concentration. In case of nitrification, the internal recycle must be switched on and the SCADA enables the change of the recirculation pump velocity (high or low).

Those are the normal control methods applied, however sometimes if the MLSS concentration is modified but effluent quality does not decrease, no changes at all are carried out.

Flow equalisation control

Another control strategy recently implemented in the SCADA is the equalisation of secondary influent flow rate. The Granollers WWTP presents important inflow rate oscillations during the day, which cause very high oscillations in the upflow velocity of clarifiers. This fact forces the secondary settler to work under continuous change and extreme conditions in moments of large solids loading. Under these conditions, the secondary settlers can easily experience losses of sludge solids, depending on the sludge blanket of the primary settler. To avoid this situation, the use of a primary settler as a flow equaliser was examined. Using this technique, when high influent flow rates occur, wastewater is accumulated in the primary settler whereas in moments of low hydraulic loading (*i.e.*, during the night) part of the accumulated wastewater is pumped to the secondary treatment. This ensures maintenance of a more stable hydraulic loading. This flow equalisation is regulated by the SCADA through a programmed sequence. Figure 10 shows the secondary influent flow rate of two days, before (November 24th, 1999) and after implementing the flow equalisation (August 1st, 2000). Indirectly, this flow lamination also results in a smoothing of the organic loading to be removed.

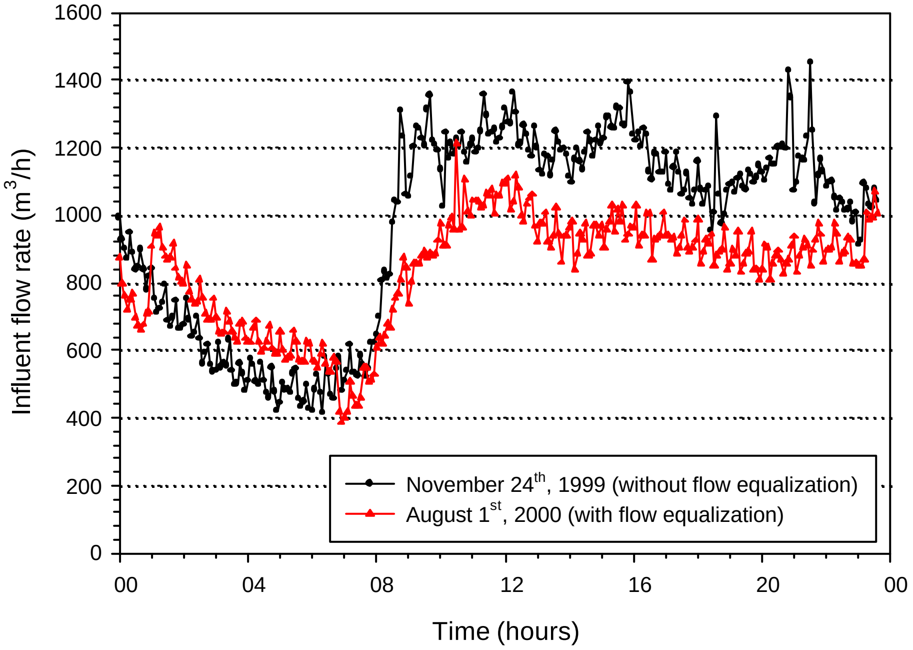

Figure 10 Influent flow rate before and after flow equalisation.

Recent control strategies on wasting rate and recirculation

A current research, still in an initial development phase, is being conducted to optimise the WAS, the RAS and N/D control. Probably these recent control strategies will be directly integrated into the Supervisory System, by-passing the SCADA. These new control strategies are:

- an adaptative control of WAS flow rate: To definitively control the oscillations of organic loading in the biological treatment (which are the cause of many operational problems of biological origin) and, because the Granollers WWTP not only collects the controlled dissolved oxygen concentration in the aeration tank, but also the air flow being supplied, we attempt to infer the instantaneous F:M ratio and the BOD entering the aeration basin. We are developing a model that could estimate the F/M ratio as a function of the water inflow, the air supplied and the last value (24 h old) of the MLSS. So far, only some preliminary results have been obtained but they are promising because we have already observed a relationship between airflow and organic loading (see Figure 11).

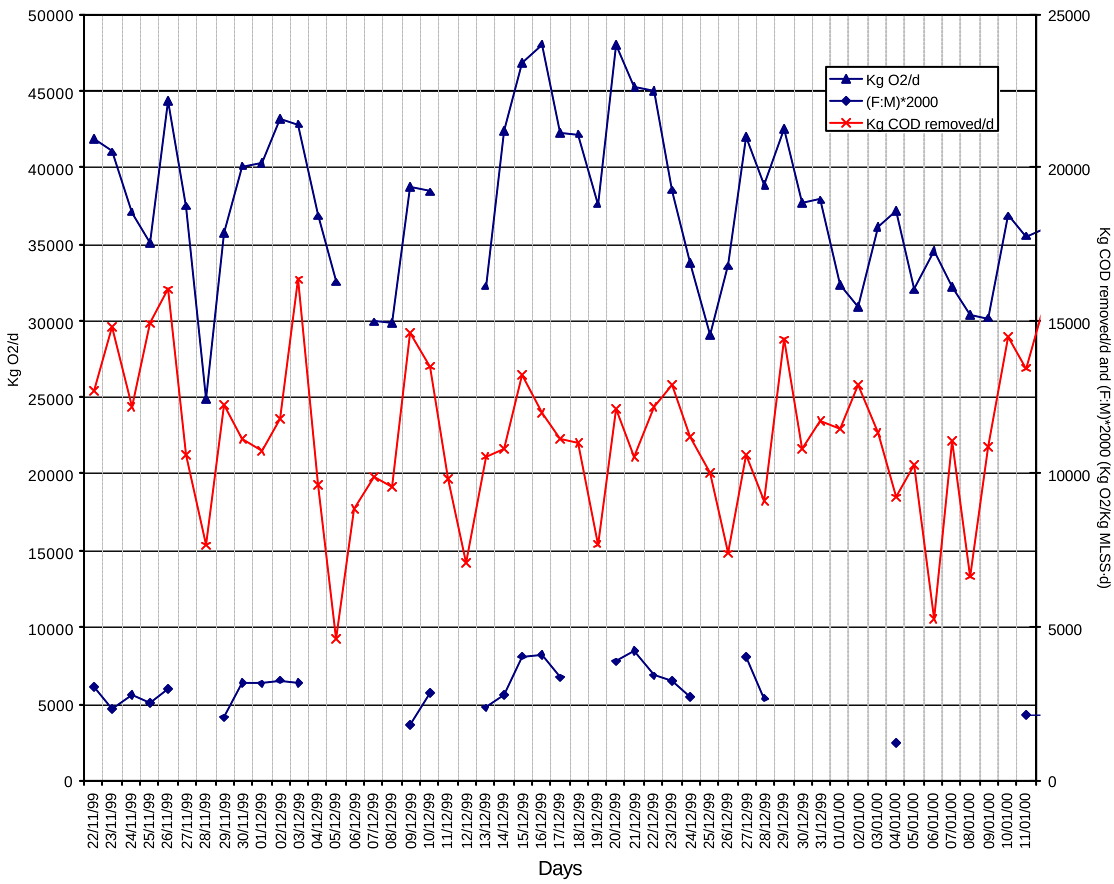

Figure 11 Relationship between daily Kg O_2/d, Kg COD removed/day and F:M.

We have also conducted an experimental sampling during a 24-h period, collecting water and sludge samples every 2 hours to monitor the MLSS, the organic load and the F:M along a day. Some relationships can also be observed among these parameters (see Figure 12). The final aim of this sampling is to find a reliable model to estimate the organic loading entering the plant and therefore, the amount of new cells of biomass generated per day. This estimation should correspond to the quantity of activated sludge to be wasted. Then, an adaptative controller for sludge wasting based on this estimation of new biomass produced, will be developed.

- a control algorithm based on fuzzy rules for the automatic establishment of the RAS rates as a function of SVI and hydraulic loading in the clarifier. There would be also some rules to ensure that some security constraints related to the maintenance of pumps are fulfilled.

- Optimisation of Nitrification/Denitrification: by using the on-line DO and RedOx potential measures to maximise nitrogen removal through recirculation flow rate control and establishment of DO set point. Few studies have been found in the literature implementing this type of control, and most of them are applied to SBR technology or completely mixed reactors [Lindberg and Carlsson, 1996b].

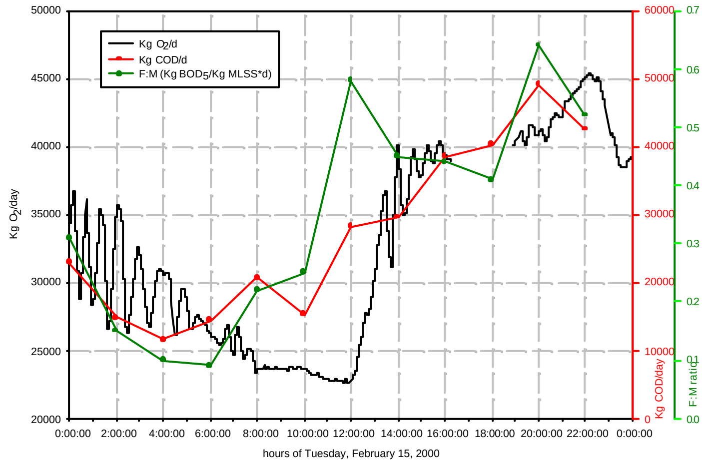

Figure 12 Relationship between hourly Kg O_2/d, Kg COD fed/day and F:M

4.1.6 Typical problems

An operational state is determined by the measurements and observations. As the process conditions change, the plant could be in different operational states. An operational state is defined as a multidimensional region, where all the process state variables and parameters are located. Thus, if some of the state variables or parameters drift away from this region, the process is assumed to be in a different operational state. An operational state can be defined as a region that includes only influent parameters and process state variables, or it can also include adequate effluent quality variables [Rosen and Olsson, 1998].

In this section, a compilation of the different operational states that usually occur in the Granollers WWTP are presented. This list was generated based on the explanations of the plant manager from the early interview sessions. Operational states include normal operation, typical abnormal situations (operational problems such as foaming, bulking…), and mechanical and electrical problems (*e.g.*, electric power shut down, pipes clogged…). Sometimes, the symptoms and the actions carried out to solve some of these problems were also indicated.

- *Rising* (denitrification in secondary settler): in order to avoid it, SRT and dissolved oxygen are decreased if nitrification is neither desired.
- Biological foams (foaming) at the aeration tank caused by *Nocardia*, *Microthrix Parvicella*, and type 1863. These foams can significantly reduce active biomass by capturing important quantities of sludge. The most severe episodes of *Nocardia* have been controlled by both an anoxic zone at the beginning of the biological reactor and by shock chlorination at the recycle sludge stream. Initial chlorine dosage tested were 4-5 Kg Cl_2/Tm VSS·d but they were later increased to 12-13 Kg Cl_2/Tm VSS·d over 2/3 days to be efficient. Sometimes, chlorination caused deflocculation but neither lysis nor encystations. Chlorination for more than 3 days resulted in ciliates mortality. Chlorination requires a microscopic monitoring to control dosage and to know when to stop the treatment. On one occasion, *Nocardia* was removed working with alternating aerobic-anoxic conditions in a whole line of the aeration tank.

- Industrial wastes: there is a significant contribution of industrial activities in the influent wastewater. These industrial wastes may include toxics, detergents, peaks of ammonia, high conductivity (values of about 10000-11000 μS/cm which caused a bacteriostatic effect in the microorganisms)…
- Rainy days with a first peak load, sometimes accompanied by discrete spills of industrial wastes.
- Storm (very low organic load after the first peak, and high hydraulic influent flow rate.
- Toxic shock or poisoning (few times and never killed the whole microfauna).
- Light filamentous bulking episodes caused by *Sphaerotilus natans*, type 021N, *Haliscomenobacter Hydrosis* and *M. Parvicella*. A very severe episode of filamentous bulking has never succeeded in Granollers. Sometimes they appear when (1) applying methods to eliminate filamentous bacteria responsible of foaming and, (2) treating high-loaded side-streams from thickeners.
- Primary settler problems in this plant have never been serious, just some presence of foams or colour due to a deficient removal of oil emulsions.
- *Strange* wastes not detected with COD or SS but with colour and odour, which favour *Nocardia* proliferation. Heavy wastes are also presented on Saturdays, provoking operational difficulties in the plant.
- Many problems from mechanical or electrical origin: obstructions of the clarifier siphon, non-return valve, too much consumption of the recycle pumps causing power shut down, polyelectrolyte dosage (polyelectrolyte polymerisation at the bottom of tank)...
- Organic overloading: from mean COD values of 400-500 mg/l to 1200, with instantaneous peaks still much higher.
- Influent peaks of ammonia. To reduce the nitrogen load, an SBR is being studied for N removal of the highly loaded side-streams from centrifuges (which could suppose a 7% of the total influent nitrogen).
- Other problems of effluent turbidity: *pinpoint*, disperse growth (sometimes caused by the chlorination), viscous bulking...

4.2 Description of the Database

Plant and laboratory operators routinely carry out an exhaustive characterisation of the influent, effluent water and sludge quality and process state variables, including both quantitative and qualitative information. Table 3 and Table 4 summarise all the available information, distinguishing the source of measurement for each variable and the sampling location.

Source	Variable	Sampling location
Analytical (off-line)	Chemical Oxygen Demand (COD) Biological Oxygen Demand (BOD) Total Suspended Solids (TSS) and Turbidity (Turb) Ammonia (NH_4^+) Total Kjeldhal Nitrogen (TKN) Nitrite/Nitrate (NO_2^-/NO_3^-) Phosphorus (P), Temperature (T) Conductivity (Cond), Greases and oils, metals, inhibitors	Influent, Primary Effluent, & Effluent
	Mixed Liquor Suspended Solids (MLSS) Mixed Liquor Volatile Suspended Solids (MLVSS) V30	Aeration Tank, & Recycle
Sensors (on-line)	pH	Influent & Effluent
	Dissolved Oxygen (DO) concentration	Aeration tank
	Flow rates (Flow)	Influent, Primary effluent, Effluent, Aeration, Recycle, Recirculation & Wasting
Global (calculated)	Sludge Residence Time (SRT), Sludge Volume Index (SVI), Food to Microorganism ratio (F/M), Hydraulic Residence Time (HRT), % COD, BOD and SS removal of primary, secondary and overall treatment	-

Table 3 Quantitative data measured in the WWTP.

4.2.1 Quantitative data

Quantitative data can be divided in:

- on-line data provided by sensors and directly acquired by the SCADA system. These data include: flow rates (influent, primary effluent, effluent, aeration, recycle, recirculation and wasting) and physical parameters like pH or dissolved oxygen concentration at the aeration tank,
- quantitative data provided by the analytical determinations of samples collected daily from different locations in the plant. These data are: organic matter measured as COD and BOD, suspended solids, turbidity, nitrogen and phosphorous in different chemical forms, temperature, conductivity, greases and oils, metals or other inhibitors, V30 and biomass concentration (MLSS and MLVSS). For a good monitoring of the activated sludge process, 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 such as sludge residence time, hydraulic residence time, sludge volume index, food to microorganism ratio and the percentages of COD, BOD and SS removal of primary, secondary and overall treatment.

4.2.2 Qualitative data

It is very important to register the qualitative information in a suitable and standardised format for an easy and effective management, retrieval and interpretation of this information and for providing understanding of the process. For example, for the non-ordered qualitative variables (*i.e.*, structure of floc), it is necessary to define the possible categories (*slightly-disperse*, *disperse*, *very-disperse* and *compact*). On the other hand, in order to ease the qualitative ordered variables interpretation (*e.g.* presence of *Nocardia* spp. or presence of *Epystilis* spp.), it is necessary to divide their interval of possible values into different ranks or modalities, *e.g.*, *none, few, some, common, abundant* and *excessive*, according to the expert criteria. The *qualitative* presence of each specie is calculated by the Supervisory System every time these data are introduced (see section 7.8.1.3). In fact, the tools utilised in the Supervisory System are able to deal with these kinds of qualitative non-numerical data and also, uncertain or approximate information.

Source	Variable	Sampling location
Floc Characterisation	Morphology, size and filament effect on structure	Aeration Tank
Protozoan and metazoan Identification & Abundance	Relative number of the different species of ciliates, flagellates, amoebae, and metazoan, unidentified ciliates, biodiversity of ciliates, Biodiversity of the microfauna	Aeration tank
Filamentous Bacteria Identification & Abundance	Relative number of the different species of filamentous, biodiversity of filamentous bacteria, total filaments (m/ml)	Aeration tank
Macroscopic observations	*In-situ* observations about plant performance, quality of biomass and settling characteristics	Aeration tank & Settler

Table 4 Qualitative data measured in the WWTP.

Thus, qualitative data include microscopic examinations of the activated sludge and daily *in situ* macroscopic observations about plant performance, quality of biomass and settling characteristics.

4.2.2.1 Microscopic determinations

The microscopic determinations are measured once a week and consist of floc characterisation, microfauna (protozoan and metazoan) identification and counting, and filamentous bacteria identification and counting.

The microscopic floc characterisation focuses on four aspects: Morphology, average floc size, filament effect on structure and overall evaluation of floc quality. Possible values of each aspect are:

- Morphology: weak or strong (referring to its consistency), regular or irregular (referring to its shape), and slightly disperse, disperse, very disperse and compact (referring to its structure)
- Average floc size: small (< 100 μm), medium (100 - 500 μm) and large (> 500 μm)
- Effect of filaments on the floc: none, slightly open floc, open floc, very open floc and bridging between flocs
- Overall evaluation of floc quality: bad, regular and good

The different species of microfauna (protozoan and metazoan) and filamentous bacteria are identified and counted. The main protozoan, metazoan and filamentous organisms monitored are next described. Protozoan organisms, based on motril characteristics, are divided into ciliates, Rhizopodes or flagellates. Flagellates are divided into Zoo flagellates (< 20 μm) and Flagellates > 20 m. Rhizopodes or Amoebae are divided into Nude amoebae and Testate amoebae. Ciliates can be divided in Bacteriophagic (feeding on bacteria) and Carnivorous (feeding on other ciliates). According to their relation with the activated sludge floc, Bacteriophagic ciliates are divided into sessile, crawling and free-swimming:

- Crawling ciliates (associated to the activated sludge floc): *Chilodonella, Acineria uncinata* , *Aspidisca cicada, Euplotes* spp….
- Free-swimming ciliates (swimming from one floc to another searching for food): *Uronema nigricans, Colpidium* spp., *Paramecium* spp…
- Sessile ciliates (attached to the floc by a stalk): they are found as individual species (*Vorticella microstoma, Vorticella convallaria, Vorticella* sp., *Vorticella infosionum, Vorticella similis*) or forming colonies. Colonial ciliates may have stalk either rigid (*Epistylis* spp., *Opercularia* spp. or *Opercularia asymmetrica*) or contractile (*Zoothammium* or *Carchesium*).

Among the Carnivorous ciliates, there are species swimming free in the bulk liquid (*Litonotus* spp., *Coleps* hirtus) or stalked ciliates that have tentacles to feed other protozoans (*Podophrya* sp., *Tokophrya*, *Acineta* spp., *Diskophrya* spp.).

Metazoans are divided into Nematodes and Rotifers.

The species of filamentous bacteria identified in the activated sludge floc include: *Zooglea Ramigera*, *Nocardia, type* 021N, *Thiothrix,* Type 0041, *Microthrix Parvicella, S. Natans, Haliscomenobacter hydrosis, Nostocoida limicola I, Nostocoida limicola II, Nostocoida limicola III,* type 0041, type 0092, type 0411, type 0581, type 0675, type 0803, type 0914, type 0961, type 1701 and type 1863.

Finally, there are four more variables obtained in the microscopic determination of activated sludge floc: number of different species of (biodiversity) ciliates, biodiversity of microfauna, biodiversity of filamentous bacteria and total number of filaments.

4.2.2.2 Macroscopic observations

The macroscopic examinations of activated sludge are the second group of qualitative data. These data refer to observational information obtained *in-situ* about plant performance, quality of biomass and settling characteristics (the V30 settling test). These variables include: presence of bubbles, foams or floating sludge in the aeration tank and/or clarifier and during the V30-settling test, appearance of the activated sludge floc, appearance of the settler supernatant/effluent, settling characteristics, sludge blanket level in primary and secondary settlers or any anomalous observation. A qualitative report of macroscopic observations was developed in cooperation with the plant manager to support plant operators with the daily *objective* recording task (see Figure 13).

PARTE QUALITATIU DIA : / / 99

Observació macroscòpica del flòcul en la prova de la V30. (1/2/3/4/5)

1 : Flòculs petits i dispersos, que decanten lentament. La seva sedimentació presenta una fase de de contracció poc definida, així com una àmplia interfase fang-sobrenedant.
2 : Flòculs més grans que s'aglomeren i comencen a caure ràpidament. Al cap de poc es forma una interfase fang-sobrenedant ben definida.
3 : Flòculs petits que s'aglomeren i cauen no lentament. Es diferencien clarament les fases fang/sobrenedant.
4 : Flòculs poc definits o esponjosos que no s'agreguen, que cauen molt lentament o queden en suspensió.
5 : Cap dels anteriors, sinó…

Sedimentació en la probeta en la proba de la V30. (1/2/3/4/5/6/7/8/9)

1 60 min. Fang que sedimenta correctament, deixant un efluent i sobrenedant clar i amb una separació entre ambdues fases ben marcada (probls.qualitat efluent deguts a clarificador)	2 30 min. Sedimentació ràpida o lenta però el **sobrenedant** queda **tèrbol o molt tèrbol** i el fang sedimentat pot aparèixer excessivament compactat, uniforme i dens.	3 > 30 min. Sedimentació ràpida però el **sobrenedant** és **moderadament tèrbol** amb **flòcul molt fi** (com agulles) en suspensió, degut a què el flòcul és més granular que floculant
4 30 min. No hi ha sedimentació del fang actiu perquè el **flòcul** és **tant petit que no flocula**	5 30 min. Probeta en la que el fang sedimenta correctament però deixa una **capa de fang** en la **superfície**.	6 60 min. Fang de color marró característic que no sedimenta o ho fa de forma molt lenta i el **sobrenedant** queda molt **clar o una mica tèrbol**. S'observa abultament o **esponjament** del **fang**.
7 60 min. El fang, que adquireix un **color fosc** i fa **olor**, sedimenta més o menys correctament, però al cap de poc minuts **flòculs grans i esponjats ascendeixen** cap a la superfície	8 30 min 1 a 2 hr Fang (amb color marró normal) que **sedimenta** més o menys **bé als 30 min però** que, **al cap de 1 o 2 h**, tot o la major part del fang **ascendeix** a la superfície, i es possible observar bombolles (de N_2) que surten del fang.	9 60 min. Fang que **sedimenta més o menys bé però** s'observen **escumes en superfície**.

Alçada del llit de fang			
Decantador primari-1	cm.	Decantador primari-2	cm.
Decantador secundari-1	cm.	Decantador secundari-2	cm.
Espessidor-1	cm.	Espessidor-2	cm.

Presència d'**escumes al reactor (B/F/N)**
B: Si, escumes blanques; **F**: Si, escumes marrons (filamentoses) ; **N**: No hi ha escumes

Presència d'**escumes al decantador secundari (G/F/N)**
G: Si, escumes greixoses; **F**: Si, escumes marrons (filamentoses) ; **N**: No hi ha escumes

Presència d'**escumes a l'arqueta de sortida (S/N)**
S: Hi ha escumes de tensoactius; **N**: No hi ha escumes de tensoactius

Flòcul en el decantador (P/G/N)
P: Escapament de flòcul petit; **G**: Escapament de flòcul gran (Desnit incont.); **N**: No hi ha flòcul en superfície

Incidències Remarcables

Figure 13 Daily qualitative report *(in Catalan)*

The first variable refers to the macroscopic observation of the activated sludge floc in the V30 settling test. Possible values are:

- small and disperse floc with slow settling. Interphase sludge-supernatant poorly defined
- small flocs with fast settling. Interphase sludge-supernatant clearly defined
- larger flocs and good sedimentation
- poorly defined or bulk flocs with slow settling
- other features

The second variable of the qualitative report refers to the settling characteristics of the plant. Possible values include:

- good settling sludge
- fast or slow settling with very cloudy supernatant
- fast settling with supernatant moderately cloudy due to very thin flocs
- no sedimentation at all due to very small flocs (that do not flocculate)
- correct sedimentation with floating sludge
- slow settling and very clear or a little cloudy supernatant, bulking sludge
- black or dark sludge that settles quite good but, in few minutes, large flocs emerge to the surface
- good sedimentation of brown (normal) sludge but, in 1 or 2 hours, most of it rises to the surface and/or presence of bubbles
- sludge that settles quite good but presents foams in the surface

The third variable refers to the sludge blanket level at the primary and secondary settlers and thickeners. The fourth and fifth variable refers to the presence of foams in the aeration basin, clarifier and effluent tank and to the presence of sludge in the clarifier, respectively. Finally, there is a place to report any other remarkable incidence (sludge or scum floating in primary settlers, abnormal odours or colours...). This qualitative report is then introduced to the Supervisory System through the interface of off-line data.

Frequency of collection.

Frequency of data collection depends on each variable and its own evolution. For instance, usually differs considerably according to the frequency of data evolution: certain variables, such as oxygen requirement in the bioreactors, involved in processes with practically instantaneous dynamics, will most likely be updated at frequent intervals of time (*e.g.*, seconds). On the other hand, other variables from more static processes will require only daily or weekly analysis (*i.e.*, COD concentration or population of microorganisms). In practice, on-line data coming from sensors are collected every few seconds while analytical results and qualitative information are measured over 24-hours integrated samples. These integrated samples are taken every 2 hours in proportion to the inflow rate. Table 5 shows the frequency of collection and type of sample for each parameter determined. Most of the analytical results are analysed daily (COD, SS, BOD) but some of them only twice a week (TKN, ammonia, nitrites, nitrates, phosphates).

To arrange the whole data available in a suitable format for the Supervisory System retrieval and processing, a significant effort has to be made to homogenise data frequency and the format in which they are collected. Because a 24-h period has been considered the most convenient time period to work with the supervisory cycle (see chapter 7), the whole data information is registered, among other time-formats, as 24-hours average values in a conventional database software.

Type	Sample	Parameter	Frequency
On-line data	-	pH, DO, flow rates	seconds
Analytical	Integrated	COD, BOD, SS, MLSS, MLVSS, V30, Cond	daily
Analytical	Integrated	NKT, NH_4^+, NO_2^-/ NO_3^-, PO_4^{3-}, P-total	once a week
Analytical	Integrated	% Sludge dryness, % Volatiles in anaerobic sludge	Punctually
Analytical	Integrated	Greases and oils, metals, inhibitors (respirom.)	when requested
Macroscopic observations	Punctual	Presence of Foam, floating sludge or bubbles, floc appearance, settling characteristics, sludge blanket level	daily
Microbiologic examinations	Punctual	floc characterisation, protozoa, metazoan and filamentous bacteria identification and counting	once a week

Table 5 Type of sample and frequency of parameters collected in the plant.

4.3 Statistical study

Once all the data is homogenised and stored, a homogenous amount of days representative of the typical plant operation were selected to carry out a statistical study for the variables that characterise influent, primary effluent, final effluent and operational parameters (334 days). This set of days contained normal process days and typical operational problems. First of all, each variable was plotted against time to detect wrong analytical determinations, not calibrated sensors or typewriting errors.

The statistical analysis was aimed to estimate average values, minimum and maximum values, standard deviations, confidence intervals and remove outsiders. As an example, Figure 14 shows the histogram of the secondary influent rate variable. Figure 14a represents the frequency of each value of secondary inflow rate, the average value and the standard deviation. Figure 14b represents the frequency with respect to the normalised flow rate. Finally, Figure 14c shows the frequency of each given value (expressed as % of total values).

The results from statistical analyses were also used both for the development of the expert system and the case-based system to support the expert in defining the qualitative modalities for each variable (to be used to define the qualitative modalities necessary to abstract quantitative data to qualitative data - see section 7.4.1).

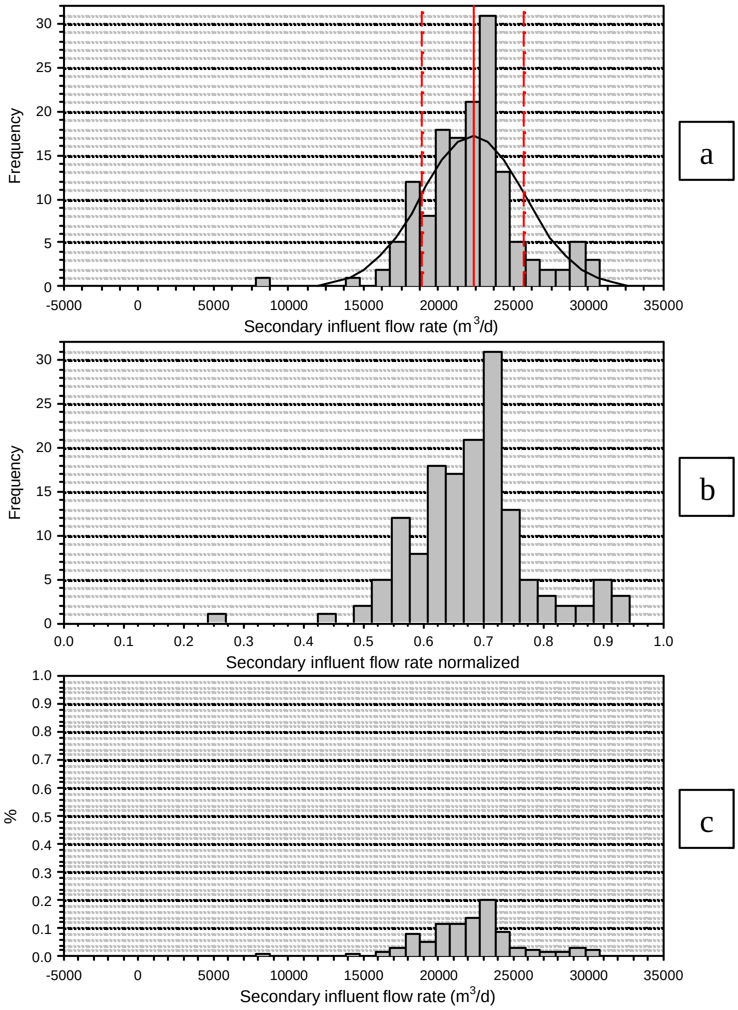

Figure 14 Histogram for the secondary inflow rate.

4.4 Conclusion

In this chapter, the actual configuration of Granollers WWTP, its current operation and control, the typical problems and most of the historical data has been presented. In spite of the improvements made in the control systems and the amount of information gathered, the Granollers WWTP plant still suffers a set of typical problems difficult to deal only with the SCADA system. The correct and fast troubleshooting of these situations requires of the experience of the plant manager and operators. The correct management of these abnormal situations and, in a higher level, the supervision of the process to avoid problem situations are the main challenges that we wanted to tackle and the main motivation for the development of an Supervisory System for an easy and more successfully management and control of the plant. In its building, some techniques from AI are used to overcome the classical control limitations (since they enable encoding of expertise and experiential knowledge) and to take advantage of the amount of data already available in the plant. Some machine learning techniques will be applied to discover *hidden* knowledge in the dataset.

Results presented in this thesis mostly come from the data collected in the Granollers WWTP; however, as the result of years of work in many different WWTPs, there are some experiments presented here that have been carried out with databases from other plants elsewhere. We think that this is not a handicap instead it is a way for partial validation of some of the tools used.

Next chapters focus on the knowledge acquisition process, the Supervisory System development and implementation and some results of its application in Granollers.

5 DEVELOPMENT OF THE KNOWLEDGE BASE

5.1 Introduction

An Expert System (ES) is defined as an interactive computer program that attempts to emulate the reasoning process of experts in a given domain -a group of processes over which the expert makes decisions-. The ES have two main modules: the Knowledge Base (KB) and the inference engine. The knowledge base includes the overall knowledge of the process as a collection of facts, methods and heuristics, which are usually codified by means of production rules. These rules take the form: IF <a set of conditions (or premises or antecedents) is true> THEN <certain conclusions (or action or results or consequences) can be (will or should) drawn (occur) >. An ES works by applying known facts to left-hand side of rules; if true, right-hand side fires and a newly fact is discovered. The inference engine is the software that controls the reasoning operation of the ES by chaining the knowledge contained in the knowledge base optimally. The order in which rules are chained depends on the method of inference used (forward or backward). Forward chaining is done from conditions, which are already known to be true, towards problem situation that those conditions allow to establish, whereas backward chaining is done from a goal state towards the necessary conditions for its establishment.

The acquisition of the knowledge included in the Knowledge Base is the core and also the bottleneck of the ES development. It involves eliciting, analysing and interpreting the knowledge that experts use to solve a particular problem. This knowledge should be represented in an easy structured-way (*e.g.*, in tables, graphs, frames or decision trees).

5.2 Knowledge acquisition

This chapter describes the knowledge acquisition process for the development of the KB of a rule-based or expert system to manage WWTPs. This ES was integrated into the Supervisory System for the Granollers WWTP supervision.

Knowledge included in the KB can be obtained from several sources. These sources can be divided into two types: documented (based on existing literature about the topic and on the WWTP database) and undocumented (that is, experiences or expertise from the experts of the process). Information can be identified and collected using any of the human senses (*i.e.* throughout interviews with the experts or reading books, journals, flow diagrams…) or with the help of machines (the use of machine learning tools to acquire knowledge from historical database). Therefore, the different knowledge acquisition methods can be classified into manual and automatic (Figure 15). In the knowledge base development of this study, different methods from both types have been used. The conventional knowledge acquisition methods (literature review, interviews and other manual mechanisms) were used in first place. To overcome the limitations of conventional methods, they were complemented with the use of different automatic knowledge acquisition methods. These last methods can be either supervised (mainly inductive learning techniques, rule and tree induction) or unsupervised (essentially Linneo^{+}, which obtain information directly from the database). Figure 15 illustrates the main sources and methods that were used to acquire both kinds of knowledge from the wastewater treatment processes.

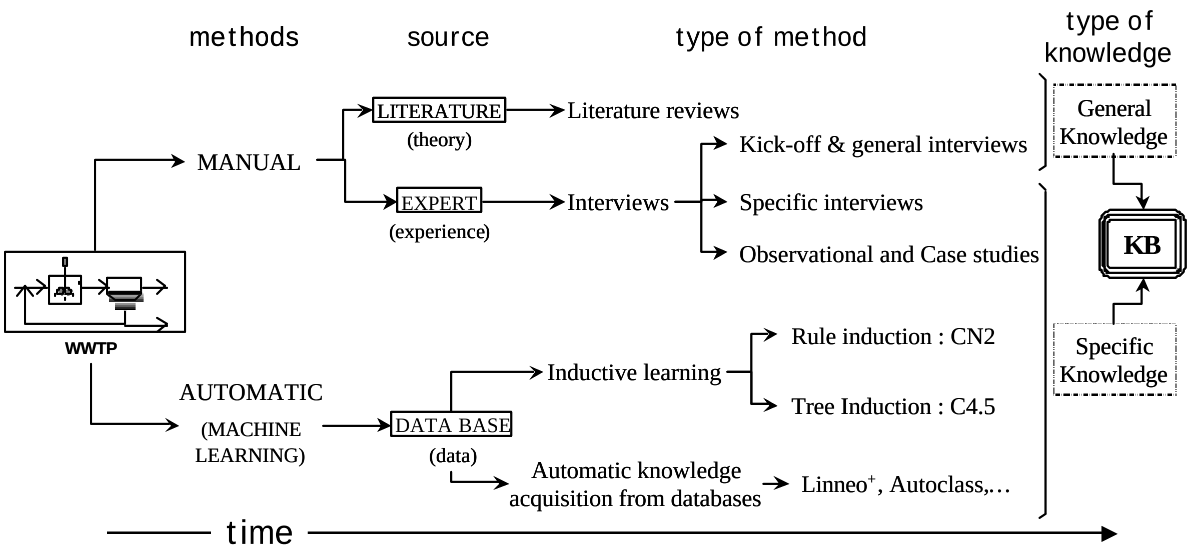

Figure 15 Classification of the sources and methods followed to acquire knowledge from WWTP

All these different sources and methods to acquire knowledge from a complex process, in this case the WWTP domain, lead to two kinds of knowledge about the process management and control to set up in the KB:

a) general knowledge, i.e. theoretical, already existing information for general WWTP management,

b) specific knowledge, *i.e.* practical, information from the particular treatment plant.

This knowledge elicitated was implemented in the knowledge base after a previous graphical representation. Among the different possibilities to **represent** the whole **knowledge** elicitated (tables, decision trees or knowledge diagrams and frames), decision trees were selected as the most suitable representation. All symptoms, facts, procedures and relationships used for problem diagnosis can be cast into a set of decision trees. These trees consist of hierarchical, top-down descriptions of the linkages and interactions among any kind of knowledge utilised to describe facts and reasoning strategies for problem solving (objects, events, performance and meta-knowledge). In other words, these logic trees represent the “causal” chain of interactions from symptoms to problems. A knowledge decision tree is also typically detailed as networks of interconnected nodes and arcs. Each node corresponds to a question related to a particular set of information (a single fact, a parameter or a condition), whereas each arc between nodes corresponds to a possible value for that information. In a decision tree, leaf nodes represent a class or diagnosis and decision nodes specify some test to carry out on a single attribute value, with one branch for each possible outcome of the test. This structured feature of interactions among the nodes of the graph allows the direct interpretation of diagnostic reasoning. From this, the translation of the knowledge contained in a branch of decision trees into a production **rule** is direct. For example, the arc between nodes A and B in Figure 16 identifies that A is the premise of condition 1 while B is its conclusion.

Figure 16 A is the premise of condition 1 while B is its conclusion

The whole heuristic rules of the process can then be easily generated by traversing each path from the root to every leaf of these decision trees, and representing them as production rules of the form IF/THEN.

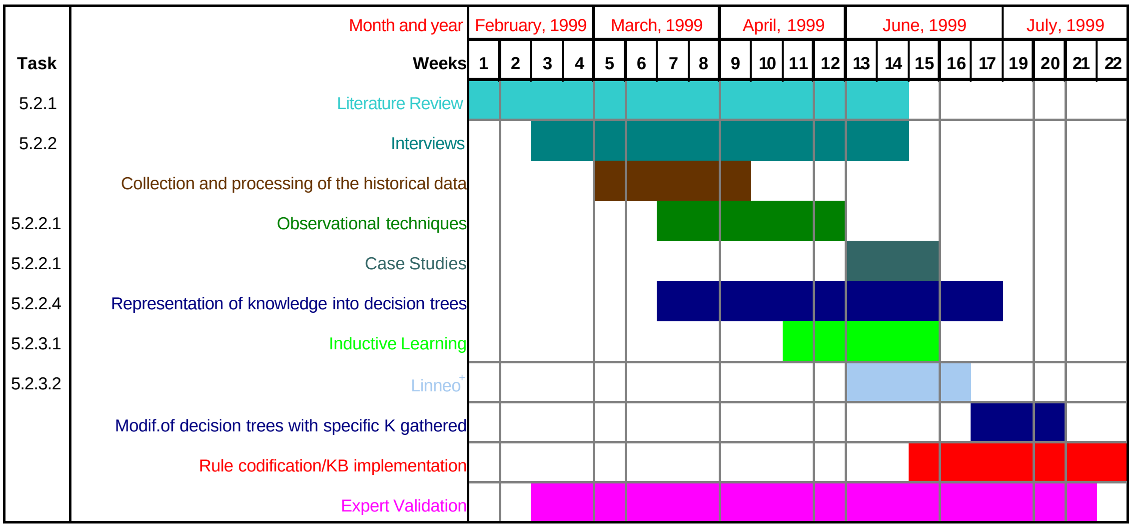

Figure 17 Gantt diagram showing the ES development.

This chapter details how the knowledge was acquired to build these decision trees for the rule-based system developed in this study. This chapter is organised as follows: section 5.2.1 briefly explains the literature review done using bibliographic sources, section 5.2.2 describes in detail the interview process, including how they were done, the knowledge elicitation and its representation and other manual acquisition methods; finally, in sections 5.2.3.1 and 5.2.3.2, we describe and discuss the automatic knowledge acquisition methods used. Each technique used in the knowledge acquisition process is described following the same scheme: a) a brief introduction from a theoretical point of view; b) some examples of its application; and c) some results obtained, emphasising its contribution to upgrade the knowledge base. Figure 17 shows the Gantt diagram for the ES development.

5.2.1 Literature Review

First of all, the knowledge contained in our first approach of the application of ES to WWTPs was reviewed from [Serra, 1994] and [R.-Roda, 1998]. Then, an exhaustive revision of the state-of-the-art in literature related to wastewater treatment plant operation, control and supervision was done with a major emphasis in the most recent advances. The objective was to extract the general knowledge for routine plant management under normal operation conditions and, specially, for common problem identification and troubleshooting (filamentous bulking, foaming, rising, toxic shock, overloading…). Literature reviews offer a wide range of problems related to this domain, along with a correspondingly wide range of causes and potential solutions to these problems. Such information can be found in instruction or operating manuals ([WEF, 1996a,b], [WEF, 1992], [Metcalf and Eddy, 1991]), in books ([Jenkins *et al.*, 1993], [Qasym, 1994], [Tillman, 1996], [WEF, 1994] [Jenkins *et al.*, 1994], [Horan, 1990], [Ekama *et al.*, 1997]…), in in-house documentation of the WWTP management companies, and in specialised journals (*Water Science and Technology*, *Water Research*, *Water SA* and other scientific and engineering journals). Other existing knowledge-based systems applied to wastewater treatment plants were also reviewed.

Nevertheless, these bibliographic sources of knowledge can quickly become dated, may be dispersed and have a lack of structure, and hence interviews with a domain expert are essential. The specifications of each WWTP can cause a failure of the general action plans. Sometimes, the experts of WWTP need to know more than the general facts and principles to solve problems. The experts usually know which sort of information is relevant to particular judgement, how reliable different information sources are and how to make hard problems easier by splitting them into sub problems. They are continuously learning new proven and validated problem-solving strategies normally acquired through years of experience (rather than formal training) without necessarily updating such knowledge into written documents. However, eliciting this kind of heuristic knowledge is much more difficult than eliciting either particular facts or general principles. Therefore, interviewing becomes the primary means of acquiring human expertise. Nevertheless, part of this bibliographical information will be integrated with plant specific knowledge within decision and action trees and later, included in the knowledge base of the expert system.

5.2.2 Interviews

First of all, a set of face-to-face interviews sessions with the expert of the plant (Granollers WWTP) was scheduled for first-hand knowledge elicitation of human expertise.

The aim of the first meeting or ***Kick-off*** **interview** [Gonzalez and Dankel, 1993] with the expert was to create a good rapport. Some tasks included in the agenda of the first meeting were:

- an introduction of the expert and ourselves (knowledge elicitators),
- an explanation of what knowledge-based systems are and how they can support in the WWTP supervision,
- a discussion of *what* will be done more than the specifics of *how* it would be done, and,
- a discussion of what is expected from the expert (in terms of time, effort and cooperation) as well as what the expert could expect from knowledge elicitator (*i.e.*, the tasks and terminals are specified into the Gantt diagram in Figure 17).

This first interview should take not more than one hour. The real knowledge elicitation process began in subsequent interview sessions. Two categories of interviews according to the type of knowledge gathered were distinguished: Orientation or **general knowledge-gathering interviews** and **specific knowledge-gathering interviews**. Nevertheless, sometimes both general and specific knowledge were obtained during the same session.

The **orientation or general knowledge-gathering interviews** were sessions addressed to gather and gain general knowledge about the general operation, control and supervision of wastewater treatment processes. These interviews were conducted with open-ended questions (*i.e.*, these questions require discussion and cannot be answered simply with yes, no, a term or a number). These kind of questions give the experts an opportunity to speak freely about their expertise, to feel more relax and allow to start identifying how the expert mind *works*. As pointed by [González and Dankel, 1993], the problem in these open-ended questions is that the expert may take *uncontrolled walks* or tangents through the domain, resulting in a waste of time and being difficult to bring the expert back to the main topic of the interview. So, *controlled walks* were desirable, although a thin line separates each other. Some orientation questions are:
Could you describe, in simple terms, what do you do?
What do you consider to be your main task?
What is the wastewater composition? and from where does the wastewater come?
Which is the main objective of a WWTP?
Which are the main problems of WWTPs?

This open-ended questioning continued through several sessions until we felt convinced that a global vision of the WWTP management and of the expert's opinion and viewpoints on the domain was obtained. Nevertheless, this shallow knowledge is insufficient to describe complex situations because refers only to surface level information. Probably it would not be explicitly coded within the KB, but sometimes it can be useful to complement the knowledge acquired from the literature review. After these first general questions, another set of questions were performed by querying more concrete issues about the particular plant (Granollers WWTP) operation:
Which is the main objective of this plant? Is it either organic matter and SS removal or BNR?
Have there been modifications in this plant? Were they expected?
Which kind of processes does the plant use (physical-chemical or biological)?
Which is the plant configuration (type of reactor, number of reactors and settlers, etc…)?
Which are the operating and control strategies conducted over the process?
Which are the main parameters used to monitor the plant performance? and to detect anomalies?
Which are the common problems that occur in the plant?
Which type of data does the plant collect (on-line, analytical, qualitative)?
How many sample points are in the plant layout? Where are they?
Which is the frequency of the data collection (seconds, hours, days, weeks)?
Which is the way to register the data collected?

The answers to these questions enable to learn about specific features of the plant. The particular characteristics of the process, including a complete description of the plant, control and operational strategies carried out, a description of the data that the system will use, the typical problems to be solved, and the criteria that the solutions must meet, were gathered to outline a shallow but necessary knowledge about the plant. An exhaustive review of the incidences occurred in the plant during the last years allowed the recognition of both the most frequent and the rare problems that occur at the WWTP. This knowledge is mainly described in the chapter 4.

After revising all the general process knowledge obtained through literature review and orientation interviews, we were able to generate a list of the situations to be considered and to establish the first relevant facts and procedures for correct troubleshooting and problem solving. Nevertheless, the real specific knowledge of the plant was obtained from the **specific knowledge-gathering interviews** and **machine learning methods**. Thus, a set of more structured and deeper interview sessions (**specific knowledge-gathering interviews**) were conducted to understand and really elicitate the specific strategies used by the expert in problem diagnosis and solving. These interviews were based on more specific questions, many of which resulted in yes/no or numeric answers (close-ended questions). They were highly directed to keep the expert focused on the problem at hand and do not allow him/her to digress from the question. Each interview session was addressed to distinct objectives. One or two typical operational problems were selected to be discussed in each session, as the fraction of knowledge to be extracted from the expert and represented within the system (real knowledge acquisition session goals). Sometimes, the deep inspection of one of these operational problems took more than one session. For this reason, every problem should be well understood by the expert being interviewed, and treated with sufficient breadth and depth to truly represent the difficulties of their control. Therefore, deeper knowledge is obtained with these interviews, which refers to the internal and causal structure of a problem and considers the interactions among the different facts of the problem. For example, one of the topics discussed in one session was the filamentous bulking problem. The goal was to identify the signals, key variables and relationships among them to diagnose a filamentous bulking problem and the corresponding action plans according to the cause. This information can be clearly identified in the final decision tree developed for filamentous bulking problem, a part of which is shown in Figure 19. The steps followed to build the filamentous problems decision tree are presented in section 5.2.2.4.

Not all the expert-knowledge engineer interactions were based on one-to-one interviews. There were also three possible types of team interviewing:

- one-to-many: one knowledge engineer and many experts. Sometimes, expertise is divided among sub-domains (one expert for each sub-domain) and the experts cooperate to solve the problem. For instance, in our study, besides of the plant manager, the plant also has an expert specialised in microbiological observations and another expert for the equipment maintenance. This kind of meetings was also used to present some partial results. These interviews become useful if several experts work closely together (advantage of synergism, synthesis of expertise, discovering of information not previously considered by the plant manager, to broaden the coverage of proposed solutions and to combine the strengths of different approaches of reasoning), but if they have too much conflicts and disagreements, then problems can arise.

- many-to-one: multiple knowledge engineers and one expert. Normally, not very useful since the expert may feel overwhelmed by the multitude of knowledge engineers. This methods was not used in our knowledge acquisition process.
- many-to-many: not really recommended since the larger the group, the harder it will be to accomplish the task of extracting knowledge. More acceptable are two-to-two meetings where the advantages of synergism and multiple observers combine. This method was not used in our knowledge acquisition process.

5.2.2.1 Other "manual" knowledge acquisition methods used

This section examines other manual knowledge elicitation techniques that are variants of the typical question-and-answer interviews. These alternatives are useful in situations when the expert finds difficulties to explain how he/she solves a problem (*i.e.*, he/she knows what to do but he does not really know how to explain it). These methods are a set of techniques that attempt to "track" the reasoning process of an expert and include: *Observational techniques, Case studies and Role-playing.*

Observational techniques

The expert is observed at work to understand and duplicate his/her problem-solving procedures when facing to a particular real problem. The on-site observation technique can be done without interacting and disturbing the expert when he/she is solving a particular problem. However, this is not a good technique for obtaining details about the process. Any doubts or questions raised from this observation, must be solved in a next question-and-answer session. On-site observation technique combined with formal interviewing enables to verify or validate the pieces of knowledge acquired. Also, the expert can be asked to perform a real task and to verbalise his/her thought about the process. That is, the expert is asked to "think aloud" while performing the task of solving the problem under observation. As an example, observational technique with interaction is used when obtaining microbiological knowledge from the expert. Although, the expert in microbiology can easily identify the state of the process through microscopic observations of the mixed liquor, he/she really has considerable troubles to verbalise it with words if he/she is not observing the sample. Therefore, this microbiological knowledge (predominant organisms in normal operation, specific organisms indicating a problem, floc formation…) should be extracted and discussed while the microscopic determination is being conducted. The disadvantages of observational techniques are that they are very time consuming and may only cover the limited number of cases presented at the plant. In addition, the expert may feel uncomfortable by being observed and perhaps behave unnaturally.

Case studies

This technique consists of selecting cases with different degrees of difficulty from historical data and presenting them to the expert for their resolution. This technique overcomes the disadvantage of the observational techniques, that is, the unpredictability of the problems that may occur in the plant. For this reason, this technique is applied to those problems that occur with low frequency (severe toxic shock or poisoning, important primary settler problems or an electric power cut). Some of these sporadic situations can be discovered in the historical database by means of the application of the automatic acquisition method, which is later described in section 5.2.3.2. Once discovered, these situations are presented to the plant manager who proposes the action plan (see section 5.2.3.2 for some examples).

Role-playing

Sometimes, the expert and knowledge elicitator can exchange roles. Knowledge elicitator (as pseudo-expert) attempt to solve a problem in the presence of the real expert who makes questions about what the elicitator is doing and why. Then, obviously, a new dialogue between the expert and knowledge elicitator can clarify and modify approaches that were thought to be proper and can discover new problem-solving strategies, which were not previously covered. This technique was not used in the knowledge acquisition process of Granollers.

5.2.2.2 Knowledge Representation

After each knowledge-gathering session with the expert and, preferably, before 48 hours, the notes from the session should be recovered, understood, and the knowledge containing examined. Then, an effort is made to transform this acquired knowledge into a form of representation that can be easily understandable by the expert. To ensure the optimal **knowledge representation**, this process is divided into two stages: **organisation** and **documentation**. The **organisation** of the knowledge gained is conducted using the input-output-middle method, which consists of:

i. Identification of the sources of information that the expert uses to detect the problem (inputs).

ii. Identification of the answers or solutions to the problem being discussed (outputs). The information collected in (i) and (ii) is mainly *descriptive knowledge* (*i.e.*, related to a specific object or fact).

iii. Identification of the links between the inputs and the outputs (the middle). These connections are the core of the expert's knowledge and are translated into the branches of every logic tree (it is the *procedural knowledge* and represents the reasoning procedures used in the problem-solving processes).

The general knowledge from literature and the orientation interviews could complement the specific knowledge obtained from the experts, especially if it does not totally cover a situation. Therefore, at this point, both the reasoning mechanisms and the action strategies from general knowledge must be incorporated, if necessary, to be organised into the final knowledge base.

Finally, the **documentation** stage in knowledge acquisition involves the important task of representing the organised knowledge in an easy and clear manner that can be understood by the expert. We usually used a "paper" record, which is the drawing of decision trees or a knowledge diagram. This *intermediate* representation facilitates its later translation into decision and action rules. As an example, Figure 18 shows the translation of the notes taken after asking the plant manager about the routine monitoring of the plant into a diagram. Nevertheless, a set of rules or a direct computer implementation can also be utilised.

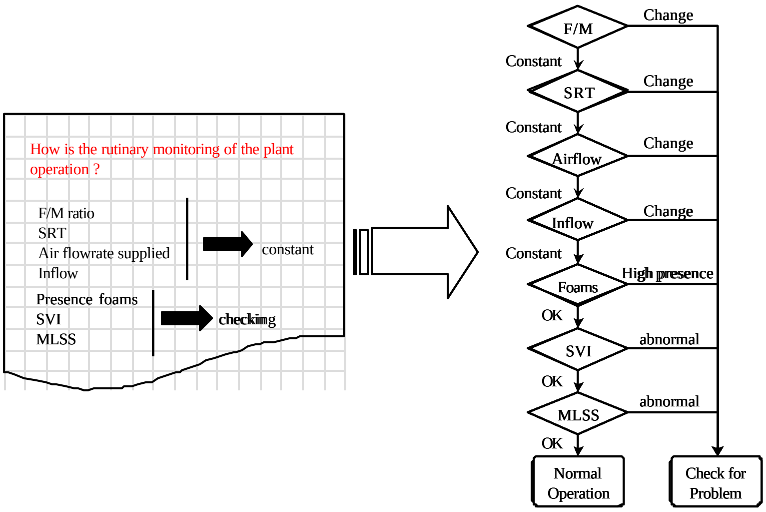

Figure 18 Representation of the notes taken during the interviews into knowledge diagrams.

5.2.2.3 Some considerations to take into account when interviewing

We should take some considerations in planning and conducting interviews. All circumstances evolving the **planning** of interviews (location, time, topic and structure of the session) are particularly important to result in successful and fruitful sessions.

- Location: it is recommended to carry out the interviews at the expert's work place (*i.e.*, the WWTP) because the expert feels more comfortable and has any kind of documentation at hand, in case he/she needs it. The only problem is the frequent interruptions.
- Schedules: The meetings are done two or three times per week and they never last for more than 2 hours. They need to be arranged one week in advance. This time frequency allows having time to *digest* the acquired knowledge, while less frequent meetings will suppose too much discontinuity. It is often difficult and undesirable to schedule long time sessions with the expert because they are usually very busy, and, moreover, concentration also decreases after 2 hours. The interviews were scheduled in the morning to avoid rapid tiring and involvement in any actual problem of the plant.
- Preparation: Before preparing the structure of the new session, the knowledge obtained during the previous interview must be *digested*. For more details about knowledge representation see next sub-section. The interview sessions are always structured following the same methodology:
  - first, there is a review of previous work, in which we check with the expert the correctness and validity of the knowledge acquired during the last interview and represented in a logic tree,
  - secondly, the establishment of the specific session objectives (one or two specific problems deeply examined) because sometimes the expert tends to turn aside from them. Identify and refine the major areas of questioning.

- sometimes, parts of the expert system prototype development are shown as a black box with inputs and outputs, without giving internal details.

In relation to how the interviews are **conducted** and **recorded**, the maximum productivity of the interview and the achievement of the desired objectives is always the major goal. Communication between expert and knowledge elicitator is attempted to be improved by minimising interruptions (*e.g.*, if a question arise us during the expert explanation, it is written down and asked once the expert has finalised his/her exposition), showing interest, taking concise notes (*i.e.*, notes consisted of summaries of the major points of the discussion but they did not include literal words from the expert), and sometimes, repeating the notes to confirm their validity. Neither video recorders nor audio recording were used. Although a complete record of the interview is guaranteed, the review of the recording would take us two or three times longer than the original session, making that a tedious and time-consuming work.

5.2.2.4 Development of the logic trees

The whole knowledge acquired was represented as decision trees, as a previous step to the rule codification into the knowledge base. For this purpose, all the general knowledge obtained through literature review (mainly) and orientation interviews and the plant specific knowledge, obtained from interviews, was reviewed, organised and synthesised in a set of decision trees. These trees include diagnosis, cause identification, and action strategies for a wide range of WWTP troubleshooting, avoiding contradictions and redundancies. These logic trees become a documentation of the expert's step-by-step information processing and decision-making behaviour. Some branches are specific and contain some particularities of the studied plant, while others are more general and can be applied to any plant. Some examples of specific actions or operation strategies of the studied plant are:

- avoid sudden oscillations of the upflow velocity in the secondary settler that could produce loss of solids. These oscillations take place due to the diurnal peak flow variations (high hydraulic loads), which switch on the second Archimedes screw and increase the influent flow rate. The use of a primary settler as equalisation basin smoothes these variations (it accumulates water during higher load periods and feeds the plant during lower load periods)
- plant recycle flows are timed to smooth rather than aggravate variable hydraulic loading (decreasing of recycle flow rate from two pumps to one when the secondary settler receive high hydraulic load) to avoid excessive turbulence in the settled sludge
- an exhaustive control of the nitrification/denitrification capacity is achieved using the DO and RedOx sensors installed along the different compartments of the aeration basin
- the wasting sludge flow rate is limited by the wasting pump and the dryer capacity of centrifuges
- the mixed liquor suspended solids is also limited by the flotation unit design specifications
- there is a limitation of the nitrification capacity in winter because low temperatures require a minimum value of sludge residence time that cannot be achieved due to the constraints of the clarifier design considerations (it would suppose a too high solids loading)

Table 6 shows the list of the situations considered. The list covers primary and secondary treatment, distinguishing between the non-biological and the biological origin of the problems. The latter origin causes a decrease in the biological reactor performance or dysfunctions in the secondary settler.

Primary treatment problems	Secondary treatment	
	Non-biological Origin	**Biological Origin**
Old sludge	White foams	Filamentous bulking
Septic sludge	Overloading (and Organic shock)	Foaming (*Actynomicetes*)
Sludge removal systems breakdown	Nitrogen shock	Deflocculation (pinpoint)
Clogged pumps or pipes	Conductivity shock	Deflocculation (disperse growth)
Low efficiency of grit removal	Storms	Slime viscous bulking
Primary high sludge density	Hydraulic shock	Toxic shock
Inadequate sludge purges	Underloading	Nitrification/denitrification
Hydraulics shock	Clarifier problems	(include rising sludge)
High solids loading	Mechanical and electrical problems	
Other mechanical problems	Transition state to some of these problems	

Table 6 List of WWTP problems considered.

The decision tree developed for detecting primary treatment problems include the following:

Old sludge: improper cycles of the sludge removal pumping

Septic sludge: septic raw sludge is common if the raw wastewater is septic, sludge is retained too long in tanks, or a poor quality supernatant liquor comes from the digesters (solids in septic wastewater settle less easily than those in fresh wastewater because biological degradation of the stale wastewater reduces the particle sizes and the gel generated tends to bring the particles to the surface)

Sludge removal systems break: sludge collectors are worn or damaged

Clogged pumps or pipes: sludge withdrawal line is plugged

Low efficiency of grit removal: sludge is hard to remove from hopper because of excessive grit

Primary **high sludge density:** the sludge density is too high for variation of solid content. A good quality for drawing should average 5%

Inadequate sludge **purges**: a high sludge volume indicates the sludge withdrawn is too thin

Hydraulic shock: hydraulic flow rates are too high (low detention times) for proper settling

High solids loading: an overload of solids causes a poor suspended solids removal

Other **mechanical problems**: scum overflow, inadequate pre-treatment of industrial wastes, floating sludge, low solids content in sludge, over pumping of sludge…

The decision trees developed for detecting secondary treatment problems of non-biological origin include the following problems:

White Foams formation: caused by non-biodegradable surfactants

Overloading: influent with high organic content (organic shock) or too much low MLSS concentration leading to a high food to microorganism ratio (process overloaded). It can cause absence of oxygen, bad settleability and low yields of removal. This decision tree also checks for possible industrial wastes (very common in Granollers), nitrogen shocks or conductivity shocks.

Storms: storms cause significant variations in flow and in suspended solids content. When rainwater is collected in the same sewage system as wastewater.

Hydraulic Shock: Excessive influent flows (typically at peak flow conditions) can cause the solids in the aeration basin and/or clarifiers to be flushed into the receiving stream (washout) if upflow velocity is too high. Storms and hydraulic shock also give a reduction in hydraulic retention time.

Underloading: influent with low organic content (low organic -loaded influent) or high MLSS concentration leading to a low food to microorganism ratio (process underloaded). Also can be caused by Imbalanced flow rates: inadequate distribution of the flow rate into the aeration basins may cause different MLSS concentrations.

Clarifier problems: inefficient sludge settling not related with biological origin (solids or hydraulic overloading, unbalanced flow rates, peak flows, high or low sludge collection rate, low skimmer efficiency, low WAS, low RAS, pipes or pumps clogged...). Some of them can lead to young or old sludge.

Mechanical and Electrical Problems: different mechanical or electrical problems of any device in the secondary treatment (electric power cuts, inadequate operation of the air supplying or distribution systems…)

Finally, the decision trees developed for detecting secondary treatment problems of biological origin include the following problems:

Filamentous Bulking: activated sludge characterised by excessive growth of filamentous bacteria, which extend from flocs into the bulk solution and interfere with compactation, settling, thickening and concentration of activated sludge.

Foaming (Actynomicetes)/foam formation: Foaming can be defined as an excessive proliferation of free and within floc filamentous bacteria with hydrophobic components, as *Microthrix Parvicella* and *Nocardia* spp or type 1863. This proliferation of hydrophobic filamentous bacteria induces the production of foam and foams of biological origin at the biological reactor surface, which could be extended throughout the secondary settler and sometimes could, provoke unintentional loss of biomass, reducing its concentration and causing bioreactor overloading. As foams float, large amounts of activated sludge solids can be trapped to surface of treatment units.

Deflocculation (pinpoint/disperse growth): small, compact, weak, roughly spherical floc particles that settle poorly (pinpoint floc) and microorganisms do not form flocs but are dispersed, forming only small clumps or single cells (disperse growth) (can lead to toxic shock). The tree includes also old and young sludge, although they can be diagnosed from other ways. The non-mechanical problems of aeration, *i.e.*, overaeration, that can cause floc breaking, or underaeration, that can avoid good floc formation, both caused either by improper F/M ratio or inadequate air supply, can also be diagnosed from this tree or from the toxic shock decision tree.

Slime (jelly) **viscous Bulking**: microorganisms are present in large amounts of exocellular slime. In severe cases, the slime imparts a jelly-like consistency to the activated sludge

Toxic Shock: situation with adverse effect on living microorganisms by some toxic substance (for example, pesticides or heavy metals). The toxic shock can be weak or severe and can lead to deflocculation of the activated sludge floc.

Nitrification/Denitrification: This decision tree includes the determination of **loss of nitrification capacity**, whenever the process begins to decrease its nitrifying capacity due to some reason; and the **rising** sludge problem, caused by denitrification in secondary clarifier that releases N_2 gas, which attaches to activated sludge flocs and floats them to the secondary clarifier surface.

Transition state to some problem: Rules that check for transition situations to any of the problems mentioned above. They were built with the same branches (*i.e.* rules) but using variables of tendency (trend variables).

The procedure followed to build these decision trees is explained in detail below (step-by-step). Every step is exemplified for the particular and representative case of the development of the decision tree for an important problem in WWTP (which is filamentous bulking problem identification and solving). A fraction of the final representation of this logic tree is shown in Figure 19.

1. **The kind and number of problem(s)** to face when searching through the branches of each tree are stated. The building of a tree able to identify and solve any settleability problem caused by an excessive filamentous proliferation was the example used. Hence, this tree covers filamentous bulking caused by any type of filamentous bacteria. In addition, some branches of the tree can lead to the exploration of other problems (foaming, viscous bulking…).

2. All the **symptoms** that can be **related to each problem** are **collected** and **listed**. One should never be satisfied with one symptom per problem, but strive for multiplicity. Some of the warning signs concern quantitative variables (*i.e.* effluent values of TSS, COD, BOD or turbidity, sulphurs at the influent, SVI, DO level at bioreactor, sludge blanket level, pH value of influent or mixed liquor, BOD to nutrient ratios and F/M ratio) while others refer to qualitative variables (*i.e.* presence of foam in the aeration basin and/or clarifier, observations of settling tests, presence of filamentous bacteria in the activated sludge floc, and floc appearance in microscopic observations).

3. Identify the qualitative **warning values** of these symptoms (high, low, abnormal and trends) and the location of the plant where they are observed, which will launch an intermediate alarm about the problem. These alarms will be translated into the *meta-rules* in the implementation of the ES. Some of these indications can clearly help in pointing out the problem.

- High values of: effluent TSS, COD, BOD or turbidity, sulphurs at the influent, SRT, sludge blanket, presence of foam, presence of filamentous bacteria, SVI.
- Low values of: F:M ratio, DO level at the aeration basin

- Abnormal values of: F:M ratio, pH, BOD to nutrient ratios, open diffused floc, supernatant in settling test (very clear or little cloudy)
- Trends: SVI and filamentous presence increasing

4. Identify the **reasoning mechanism** of the expert to diagnose the problem. This step involves the detection of the key variables to be checked when the intermediate alarm is launched, and the relationships between these variables and the problem to be inferred (*i.e.*, to spot the order in which they will be checked and the qualitative values to conclude the problem). In the bulking example, the key variables, their checking order and values to definitively infer the filamentous bulking are: Normal activity of the microfauna, high values of SVI, and numerous presence of filamentous bacteria.

5. Detect any **intermediate facts** or values that will lead to other decision trees. For example, the inactivity of microfauna, except for flagellates, indicates a possible toxic shock; a normal activity of microfauna, but low or medium SVI values, could indicate a possible foaming or other problems interfering sludge settling capacity (hydraulic shock, overloading…); a high value of SVI, but few presence of filamentous bacteria, could indicate viscous bulking; a high value of SVI, but balance between floc-forming and filamentous bacteria, could indicate a transition to a bulking situation, rising or deflocculation problem.

6. Identify not only the general **causes** suggested in the literature (low DO level, low F/M ratio, oscillations or low pH, nutrient deficiency, high content of sulphurs), but also the specific origin of each one. For example, the plant studied presents a significant low F/M ratio resulting in filamentous proliferation when more than two consecutive days of holidays occur (*e.g.*, Christmas or Easter vacations, an extra day off work after a weekend…). This is due to the fact that the wastewater treated by this plant has a significant contribution from industrial activities.

7. Often, the general **actions** suggested by literature to solve a problem do not fit well or cannot be applied or adapted. In that case, the particular strategy proven and validated by the manager of the studied plant must be collected. The action plans can be specific and/or non-specific depending whether the cause is well determined or not. For example, for solving a filamentous bulking problem caused by the filament type 021N due to a low F:M ratio, the utilisation of an anoxic zone to induce the *selector effect* could be recommended as a general action, but this method has been shown not to be really effective for type 021N control in Granollers WWTP. Instead or at least, as complement, a gradual increase of wasting rate is needed.

8. Drawing the logic tree and checking it with the head of the plant. This step, that could be long and iterative, involves modification, re-draw and checking again every inference path, and is part of the partial expert system validation.

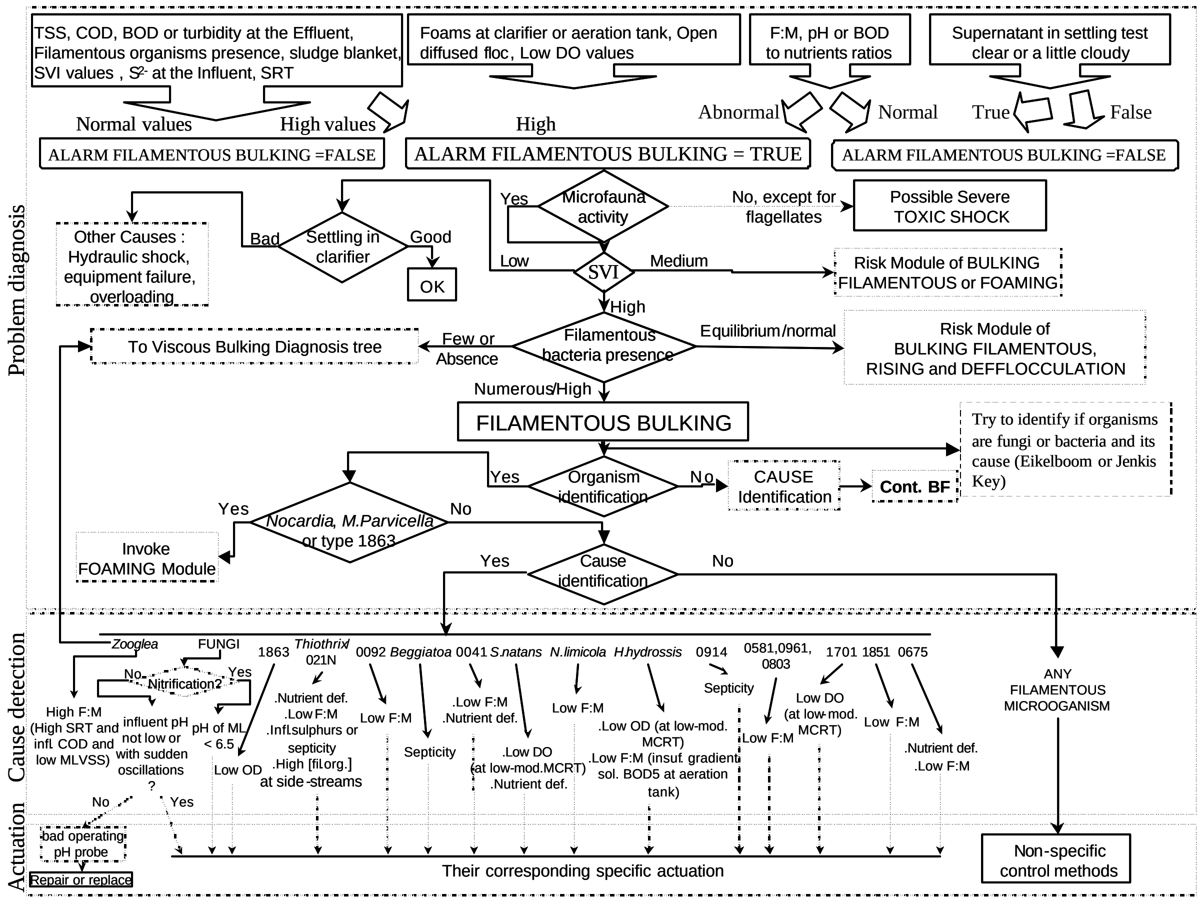

Figure 19 Decision tree for bulking filamentous problems.

The inference can start from all kind of data (qualitative or quantitative, chemical or biological), being possible to explore different branches to reach the same conclusion. This feature of the knowledge-based systems allows the evaluation of the process despite the lack of some relevant data. The whole decision trees can be found at the appendix.

Despite of the benefits from the experts' interviews, interviews present some limitations:

- experts do not find it easy to formulate how to solve the day-to-day problems. Some experts often have a hard time verbalising their expertise. Part of the reason is that they perform the tasks very automatically and subconsciously. However, they do know what to do when it comes time to solve the problem. Moreover, poor structured domains, like wastewater treatment processes, are even more difficult to explicit.
- experts express a subjective and incomplete point of view (*i.e.*, they may forget to specify certain pieces of knowledge, which may result in ambiguous information). Experts tend to emphasise recent, first-hand experience providing a limited and potentially biased view of the domain. They tend to describe how the task "should be done" rather than "how it is really done". They describe better specific cases than general terms. Moreover, experts may change they behaviour when they are being observed or interviewed.

These difficulties could make the interviews a slow process with a quite poor productivity (*i.e.*, from 2 to 5 rules/session). This makes the knowledge acquisition expensive and sometimes, unreliable, as pointed by [Jackson, 1999]. Moreover, an efficient knowledge acquisition process requires relevant knowledge that could be scattered across several sources, and therefore, not only collected from expert interviews. A side from undocumented knowledge and literature review, another documented source that must be explored is the historical database of the plant. However, it is difficult to recognise specific knowledge when it is mixed with irrelevant data using only manual or statistical techniques.

All these problems have led researchers to look upon specific knowledge acquisition as "the bottleneck problem" or stepping-stone of expert systems' developments. This is especially true when the expert system is built to manage and supervise a wide and ill-structured field like real WWTP. The intention of overcoming all these caveats and limitations in expert interviews and to take advantage of the historical database have led researchers to try to automate the process of knowledge acquisition by means of two main techniques:

- semi-automated knowledge elicitation from a person-machine dialogue interaction and,
- by the exploitation of some machine learning methods to acquire relevant, objective and specific knowledge from the historical database of a complex process.

The first one is here briefly introduced, however only some tools from machine learning methods were used in this study. In the semi-automatic knowledge acquisition methods, the expert's knowledge is transferred to a computer program as a side effect of a person-machine dialogue. This machine-based rule induction enables the expert to directly interact with an expert system to facilitate him/her structure the knowledge in a logical manner thereby facilitating the generation of a set of domain specific rules [Gonzalez and Dankel, 1993]. These systems allow overcoming some of the difficulties and result in less "noise" introduced into the KB. The first of these techniques was developed by Shaw and Gaines [Shaw, 1982] inspired in the repertory grid developed by [Kelly, 1955]. Other developed systems include KAT [GUS2000, 2000] and Auto-intelligence [Parsaye, 1988].

5.2.3 Automatic or Machine Learning Methods

These techniques enable intensive database exploration and reduce the need of an expert, trying to increase knowledge productivity and quality. Nevertheless, at the last, the knowledge acquired must also be reviewed and modified by the expert. There are two main types of machine learning methods: supervised methods (mainly **inductive learning**) and unsupervised techniques for an **automatic knowledge acquisition from databases**.

In the next sub-sections, only the machine learning methods used are explained, although there are more systems of each type in the bibliography. A special emphasis is placed on the unsupervised learning tool developed by the AI research group of the *Universitat Politècnica de Catalunya* (Linneo$^+$, [Béjar *et al*., 1997] and [Sànchez-Marrè *et al*., 1997b]). Linneo$^+$ was used to alleviate the knowledge acquisition "bottleneck" since enables to extract objectively the most relevant information contained in the database through an automatic acquisition process. Figure 15 shows the machine learning methods used in the automatic knowledge acquisition.

5.2.3.1 Inductive learning (supervised methods)

These systems are programs capable of learning from examples by a process of generalisation. These systems aid the knowledge acquisition effort by creating a set of rules or decision trees from example cases where the **outcome is known** (training set). The training set helps the system to identify the relevant concepts. Therefore, these machine learning techniques are defined as **supervised.** The rules or decision trees can then be used to assess other cases where the outcome is not known (test set or real cases). There is a great variety of learning systems but we will focus on C4.5 [Quinlan, 1993], a suite of programs for constructing decision trees, and CN2 [Clark and Niblett, 1989] and [Clark and Boswell, 1991], a system for rule induction. The results presented here for tree and rule induction refer to the specific knowledge acquisition process to develop the KB for another WWTP of Catalonia, therefore the database used is not that from Granollers.

Induction of trees

Description of the technique: Data describing a real system, represented in the form of a table, is used to learn or automatically construct a decision tree. In the table, each row (case or example) has the form: ($x_1, x_2, ... x_N, y$), where x_i are values of the *N* attributes (*e.g.*, flow rate and pH of influent, presence of foam at the aeration tank) and y is the value of the class (outcome or process state). Classification trees [Breiman *et al*., 1984], often called decision trees [Quinlan, 1986], predict the value of a discrete dependent variable with a finite set of values (called class) from the values of a set of independent variables (called attributes), which may be either continuous or discrete. The induced (learned) decision tree has a test in each inner node that tests the value of a certain attribute, and in each leaf a value for the class. Given a new example for which the value of the class should be predicted, the tree is interpreted from the root. In each inner node the prescribed test is performed and according to the result of the test the corresponding left or right sub-tree is selected. When the selected node is a leaf, then the value of the class for the new example is predicted according to the class value in the leaf.

The common way to induce decision trees is the so-called Top-Down Induction of Decision Trees (TDIDT, [Quinlan, 1986]). Tree construction proceeds recursively starting with the entire set of training examples (entire table). At each step, the most informative attribute is selected as the root of the (sub)tree and the current training set is split into subsets according to the values of the selected attribute. For discrete attributes, a branch of the tree is typically created for each possible value of the attribute. For continuous attributes, a threshold is selected and two branches are created based on that threshold. For the subsets of training examples in each branch, the tree construction algorithm is called recursively. Tree construction stops when all examples in a node are of the same class (or if some other stopping criterion is satisfied). Such nodes are called leaves and are labelled with the corresponding values of the class. An important mechanism used to prevent trees from over-fitting data is tree pruning. Pruning can be employed during tree construction (pre-pruning) or after the tree has been constructed (post-pruning). Typically, a minimum number of examples in branches can be prescribed for pre-pruning, and a confidence level in accuracy estimates can be prescribed for leaves for post-pruning. A number of systems exist for inducing classification trees from examples, *e.g.*, CART [Breiman *et al.*, 1984], ASSISTANT [Cestnik *et al.*, 1987], and C4.5 [Quinlan, 1993]. The latter is one of the most well-known and widely used decision tree induction systems and, thus, it was used in the knowledge acquisition process of this study.

<u>Results:</u> The decision tree depicted in Figure 20 was induced using the whole dataset (243 days) and attributes available (63). Nevertheless, C4.5 only uses 24 attributes, 14 qualitative variables and 10 quantitative attributes. It is interesting to notice the predominance of the qualitative variables over the quantitative variables. The trees use qualitative variables concerning not only to the number and diversity of microorganisms, but also to some subjective features like presence of foam in the aeration tank (ESC-B) or appearance of the effluent (ASP-AT).

The numbers in brackets for the leaves of the C4.5 tree specify the number of examples in the leaves For example, *c1* (66.9/7.2) means that there are 66.9 examples in the leaf, of which 7.2 are not of class *c1* (the remaining 59.7 are examples). Fractional examples are due to unknown values. Zeros appear when dealing with discrete multi-valued attributes: these are the so-called *null* leaves. They indicate that there were no examples in the training set that satisfy *all* the conditions leading to that leaf (but there were some that satisfy all but the last). The branches with higher accuracy correspond to those predicting large classes (*e.g.*, class#1 with 89.2% and class#2 with 92.7%) and medium classes (*e.g.*, class#11 with 92.3%, class#10 with 86.1% and class#17 with 73.3%. The overall accuracy, estimated in a 10-fold cross validation, was 63.51%.

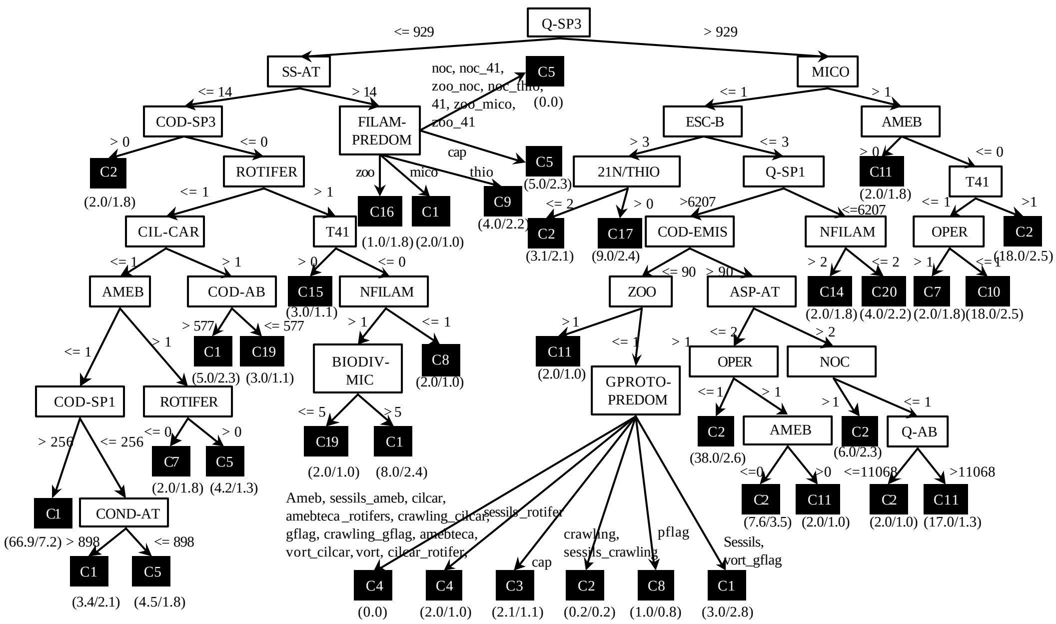

Figure 20 Tree generated by C4.5 given all 63 variables

Another tree was induced using the whole dataset (243 days) but only 19 attributes, which were the most relevant variables according to expert opinion. In this case, the overall accuracy slightly improved (65.11% cross-validation average), but understandability greatly improved. The new C4.5 tree induced was easier to interpret from the expert point of view than the first one (Figure 20) because it was smaller and it did not use attributes that the expert would not use to distinguish among the classes.

Rule Induction

Description of the technique: Given a set of classified examples, a rule induction system constructs a set of if-then rules. An if-then rule has the form as <IF condition THEN conclusion>. The condition contains one or more attribute tests of the form $A_i = v_i$ for discrete attributes, and $A_i < v_i$ or $A_i > v_i$ for continuous attributes. The conclusion part has the form $C = c_i$, assigning a particular value c_i to the class C. We say that an example is covered by a rule if the attribute values of the example obey the conditions in the IF part of the rule. The rule induction system used was the CN2. The CN2 uses the covering approach to construct a set of rules for each possible class c_i in turn: when rules for class c_i are being constructed, examples of this class are positive, and all other examples are negative. The covering approach works as follows: CN2 constructs a rule that correctly classifies some examples, removes the positive examples covered by the rule from the training set and repeats the process until no more examples remain. To construct a single rule that classifies examples into class c_i, CN2 starts with a rule with an empty antecedent (if part) and the selected class c_i as a consequent (then part). The antecedent of this rule is satisfied not only by those of the selected class, but also by all examples in the training set. Then, the CN2 algorithm progressively refines the antecedent by adding conditions to it, until only examples of the class c_i satisfy the antecedent. To allow for handling imperfect data, CN2 may construct a set of rules, which is imprecise (*i.e.*, does not classify all examples in the training set correctly). Both the structure (set of attributes to be included) and the parameters (values for discrete attributes and boundaries for continuous ones) of the rule are determined by CN2 itself. In a extreme case, a maximally specific rule will cover (be supported by) one example and hence have an unbeatable score using the metrics of apparent accuracy (scores 100% accuracy). Apparent accuracy on the training data, however, does not adequately reflect true predictive accuracy (*i.e.*, accuracy on new testing data). It has been shown that rules supported by few examples have very high error rates on new testing data.

CN2 handles examples that have missing values for some attributes in a relatively straightforward fashion. If an example has an unknown value of attribute *A*, it is not covered by rules that contain conditions that involve this *A* attribute. However, this example may be covered by rules that do not refer to attribute *A* in their condition part. For more details about CN2 refer to the appendix.

Results: a set of rules was induced with all the examples in the data set (243 examples) and 44 attributes selected by the CN2 algorithm. Some of these rules are explained and commented below. When trying to predict large classes, rules obtained were larger than those covering medium-size classes but the accuracy was also lower. The rules for class#1 and class#2 had most physical and chemical sense and were easiest to interpret by the expert. The plant manager easily identified in the antecedents some of the variables that he/she used in his/her heuristic checking process. The following rules are examples of rules induced on the whole dataset of 243 examples for predicting class#1 and class#2. The numbers in brackets for CN2 rules refer to the right examples covered from the total of the class.

IF Q-AB (influent flow rate) < 9083.00
AND Q-SP3 (biological by-pass) < 2227.00
AND COND-AT (effluent conductivity) > 847.00
AND CIL-CAR (carnivorous ciliates) < 0.50
AND AMEB (Amoebae) < 0.50
THEN WWTP-operating class = class#1 (Normal operation in winter days) (47/81)

IF TERB-AB (influent turbidity) > 123.50
AND Q-SP1 (primary effluent) > 6223.50
AND Q-SP3 (biological by-pass) > 3467.50
AND 33.00 < DQO-AT (effluent COD) < 82.00
AND COND-AT (effluent conductivity) < 1330.00
AND NOC (presence of *Nocardia*) > 0.50
AND P-FLAG (flagellates < 20 µm) < 3.50
THEN WWTP-operating class = class#2 (Normal operation in summer days) (38/55)

The rules covering medium classes appeared to be better in classification performance. For example, the next rule predicts Foaming due to *Microthrix Parvicella*:

IF Q-AB (influent flow rate) < 10924.50
AND Q-SP3 (biological by-pass) > 1030.00
AND NOC (presence of *Nocardia*) < 1.50
AND MICO (presence of *M.Parvicella*) > 1.50
THEN WWTP-operating class = Foaming due to *Microthrix p.* (17/17).

In those classes represented only by one or two examples, the induced CN2 rules utilised variables which did not seem to be the most discriminant, according to the criteria of the expert (plant manager of the WWTP), but they had higher accuracy (on the training data). For example, the pH in the influent is usually not a very informative attribute, except for extreme values over 8.5 or under 6.5, which was not the case in the rule predicting the class *Bulking sludge.*

IF pH-AB (influent pH) < 7.40
AND FILAM-DOMI (predominant filamentous organism) = *Thiothrix*

THEN WWTP-operating class = Bulking sludge (caused by *Thiothrix*)(3/3)

The average predictive accuracy of this set of rules over the 10-fold cross validation was 63.98%. Then, a new set of rules was induced using only 19 attributes, which were the most relevant variables according to expert opinion. In this case, classification accuracy slightly improved (65.45% cross-validation average), but understandability and ease of interpretation from the expert point of view also greatly improved. Attributes hardly used by the expert did not appear in the second set of rules. This held even more for rules covering small classes. As a general conclusion on the induced rules, it can be noticed that the qualitative variables have an important role when diagnosing the state of the plant. For a comparison between C4.5 and CN2 induced patterns together with *k*-NN methods and Case-based learning refer to section 8.4.2.1 or to [Comas *et al.*, 2000a].

What is obtained from tree Induction and rule Induction? A decision tree that can easily be codified as decision rules and a set of more specific decision rules that can be implemented in the knowledge base of the expert system, respectively. Some of these decision rules complement, replace or upgrade the diagnosis and action rules making the knowledge base of the expert system much more specific. These knowledge patterns extracted from data have been enhanced and made more useful with the experts' assistance role in the inductive learning process, as illustrated with the experiments done. The expert role in the experiments conducted with the inductive learning tools C4.5 and CN2 was to select the most relevant variables (*i.e.*, reduce the amount of variables) and to interpret and validate the rules and trees induced. The latter step includes indicating which tree branches or rules made sense and which did not from his/her point of view: That is, the way in which induction tools use and rank the importance of attributes may not be exactly the way that a human expert would do it. Interpretation involved an examination of the reasons for accuracy and understandability, which also changed as the attributes used changed, and finally, looking for new knowledge in the rules and trees induced. Obviously, the predictive accuracy of the inductive methods is also a very important parameter, as well as other quantitative measures of performance such as the size of both the number of examples used and the number of attributes used for the inductive generalisation. But, for example, if the knowledge extracted from the data is very accurate, but it does not make sense to the final end-user, it will probably not be used. In conclusion, it can be stated that the experts, who are supposed to be the final end-users of real-world applications, should be considered in the inductive machine learning methods as much as possible. However, most of the inductive learning algorithms and techniques do not take into account the experts' knowledge very much.

Nevertheless, there are also some difficulties in induction learning; that is, the method is only good for rule-based, classification-type problems, and the number of “sufficient” examples needed is very large.

5.2.3.2 Unsupervised Methods (Automatic Knowledge Acquisition From Databases)

In this section, we present the development of a methodology based on the automatic knowledge acquisition from the database of a process. The basis of this methodology, described in [R.-Roda *et al.*, 2000a], consists of a four-step process: data handling, classification, interpretation, and codification (see Figure 21). The classification step involves the use of an automated or semi-automated machine learning tool for an automatic classification of the historical database to obtain specific knowledge of ill-structured domains, while the whole process requires the supervision of the expert of the process. From this automatic classification, we obtain a set of clusters that can then be labelled as typical operational states. In the classification step of this study, we used the machine learning tool called Linneo+ to acquire the specific knowledge from WWTP databases. Linneo+ is a semi-automated knowledge acquisition tool for ill-structured domains that works incrementally with an unsupervised learning strategy. This strategy accepts a stream of observations and elucidates a classification scheme on the data set. The **Linneo+ methodology** could be considered as an iterative **clustering** method, that determines useful subsets of data, assuming that observations vary in their membership degree with regard to each possible class, and with **validation** from an expert to accept or reject the resulting clusters. In this study, each subset or class represents a group of days characterised by a particular situation of the facility.

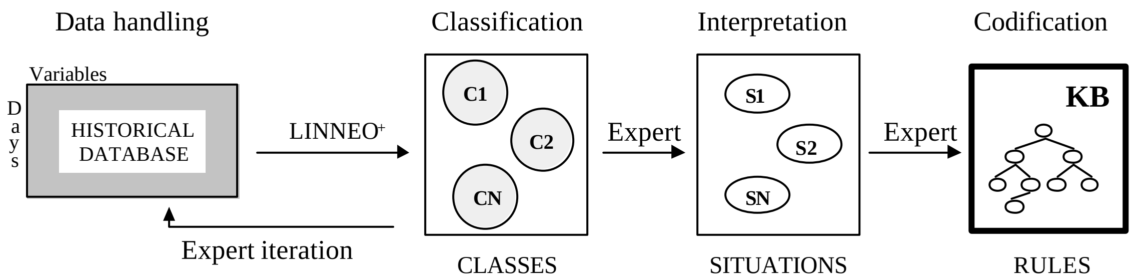

Figure 21 Scheme of the specific knowledge acquisition process, outlining the main developmental steps.

A detailed explanation of each step of the specific knowledge acquisition methodology using Linneo+ applied to the Granollers WWTP is next discussed.

Automatic knowledge acquisition methodology of Linneo+

Data handling step. The amount of historical days selected has to be representative of the most common situations that occur in the process. The time period selected must contain a set of homogeneous data adding real information about the process state and usually analysed, and avoiding few informative variables. In this study, the historical database covered a representative period of 334 consecutive days. Data from each day was considered as a particular data set. It is important to know any incidence occurred during this period that could affect or hide the registered information (such as incorporation of new sensors, incorporation of new analysis, changes in plant configurations, treatment of leachate, mechanical failure, etc…). This identification was achieved by interviews with the expert. Variables considered in the database correspond to those listed in Table 3 and Table 4 (qualitative information). The most relevant feature of the database was the high occurrence of missing values, especially for qualitative variables. Nevertheless, consideration of qualitative information was of critical relevance in this study because of its great influence on the activated sludge characterisation and behavioural understanding.

Sampling location	Variables
Influent	Flow, pH , COD, BOD, TSS, TKN, NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, Cond
Primary Effluent	Flow, By-pass flow rate, pH, COD, BOD, TSS, Cond
Aeration Tank	MLSS, MLVSS, MLSS-Rec, SVI, F/M, Qualitative information (including floc characterisation, biodiversity, microfauna and filamentous identification and abundance, and operator observations).,
Secondary Effluent	Flow, pH, COD, BOD, TSS, TKN, NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, Cond, Qualitative observations
Global	WAS, RAS, SRT, HRT

Table 7 List of the relevant variables that were classified to acquire specific knowledge

A previous statistical analysis was carried out to filter some signals and to remove redundant variables of the database. Then, a careful selection of the most relevant variables was done in agreement with the plant manager criteria. Table 7 shows some of the 78 variables that were finally selected. This final database was then structured in a homogeneous matrix, which contained the days in rows and the variables in columns.

Classification step. Once the historical database of the WWTP was structured in a summary matrix with variables in columns and days in rows, it was fed to Linneo⁺ to conduct the classification steps. Linneo⁺ works by defining a space of *n* dimensions, where *n* is the number of variables included in the database (78 in this study). Within this 78-dimension space, all days were grouped in different hyper-spherical classes, which were specified by a centre and a radius (the size of the class). To establish the limit for a day to belong to a certain class, the software uses a "distance" criterion. At the beginning of the classification process, the classes are still undefined, thus the first day is taken and placed within the space to form the first class. The centre of this class is calculated based on the values of the variables that describe the day. Then, the second day is placed within the same space. In the case, the centre of the second day is close enough to the centre of the first day, then the two days are considered in the same class, being its centre re-calculated with the mean values of the variables from both days. If the distance between the two days is too large a new class is formed. Linneo⁺ offers a previous data analysis tool to iteratively estimate a radius, which let us obtain a reasonable number of classes.

In this study, Linneo⁺ used a radius equal to 4.1 and the generalised Hamming [Dubes and Jein, 1988] as distance criterion. Based on this radius value, 13 classes were obtained from the WWTP database. These classes corresponded to a reasonable number of differentiated situations clearly identified and labelled by the experts. Some examples of the results from the classification step are shown in Table 8, with the values of the most relevant variables corresponding to the centre of classes 1, 9 and 10.

Interpretation and labelling step. Once the classification process is done it is necessary to examine and interpret all the classes identified by Linneo⁺. The plant manager should do the interpretation and the labelling. Based on his experience he related the characteristics of each class to a particular episode of the WWTP during the period of time considered in the database. Table 9 shows the list and interpretation of the twelve classes, some of them containing also a set of sub-states, and the number of days belonging to each class.

Sampling location	Variables (units)	Class #1	Class #9	Class #10
Influent	Flow (m^3/d)	23340	23225	18020
	COD (g/m^3)	794	894	617
	TSS (g/m^3)	291	327	186
	NH_4^+ (g/m^3)	86	*Nil*	230
Primary effluent	COD (g/m^3)	513	687	440
	TSS (g/m^3)	125	168	107
Aeration Tank	MLSS (g/m^3)	2391	2335	2400
	Dominant protozoa	Sessile ciliates	*Opercularia* and *Gimnamebae*	Sessile ciliates
	Dominant filamentous	None	None	Nocardia spp.
	Diversity of ciliates	1.5	0	0.6
Effluent	COD (g/m^3)	155	250	113
	TSS (g/m^3)	30	43	30
Global	SVI (g/ml)	108	24	103
	SRT (d)	7.25	?	7.26
	F/M (Kg BOD/Kg MLSS·d)	0.54	0.25	0.53

Table 8 Values of the most relevant variables for classes 1,5 and 8 from the classification step.

Class 1 is the most common situation (*i.e.*, highest number of days). This class was labelled as normal or correct plant operation. Class 2 is quite similar to class 1 but with optimal operation which is reflected in a better effluent quality. Classes 3, 4 and 5 have abnormal loading rates. Class 3 refers to those days with higher loading rates than expected (organic overloading) but with also a high value of MLSS. Class 4 corresponds to an organic shock (high load versus normal MLSS). Class 5 contains days with a high influent rate combined with a dilution of the contaminants (rainy and stormy days). Class 6 is characterised by a low loading rate with a normal influent rate (underloading) together with a partial nitrification.

Class #	# of days	Interpretation
1	203	Normal WWTP-operation days (2 sub-states): • Days with normal WWTP-operation
2	71	• Days with better WWTP-operation (better effluent quality)
3	12	High loaded influent (but with very high MLSS)
4	1	Organic overloading (organic shock)
5	6	High influent with dilution of contaminants (2 sub-states): • Rainy days
	2	• Storm days (hydraulic overloading)
6	1	Organic underloading and partial nitrification
7	1	Partial nitrification (nitrite accumulation)
8	2	Rising and phosphorous removal
9	2	Deflocculation with effluent turbidity (probably toxic shock)
	2	Deflocculation (effluent turbidity due to small-flagellates)
10	1	Ammonia shock
11	2	Filamentous Bulking affecting the effluent caused by *S.natans* and *M.Parvicella*
12	3	Foaming caused by *Nocardia* and Bulking caused by S.natans and *Haliscomenobacter h.*
13	1	Foaming caused by *Nocardia* (very low SRT and very high WAS)
	12	Foaming caused by *Microthrix* (with normal microfauna diversity, without flagellates)
	4	Foaming caused by *Microthrix* & type1863 (low ciliates diversity and small flagellates dominant)
	8	Foaming caused by *Nocardia* & type1863 (very low ciliates diversity but flagellates not dominant)

Table 9 List of classes obtained by Linneo+, and the corresponding interpretation of them according to the criteria of the plant manager.

Classes 7 and 8 correspond to periods of partial nitrification episodes (nitrite accumulation) and rising sludge (*i.e.*, uncontrolled denitrification in the secondary settler) and phosphorous removal, respectively. Class 9 (deflocculation) describes a situation with poorly settling and compacting activated sludge. This situation is caused by the total absence of filamentous organisms leading to small flocs (pinpoint floc) or by a very low production of exopolymer (bioflocculation does not occur). Class 10 was interpreted as an ammonia shock leading to a very high nitrogen loaded influent. Classes 11, 12 and 13 correspond to abnormal situations due to the proliferation of different filamentous bacteria leading to different settling interference depending on the causative bacterial species: Bulking sludge (if the dominant filamentous bacteria was *S.natans*), Foaming (associated with the presence of *Microthrix Parvicella* or *Nocardia*). Among these classes, class#11, labelled as filamentous bulking sludge, describes days where settleability of the activated sludge was significantly poor (*i.e.*, high values of SVI), leading to a poor clarified effluent with loss of solids (high values of COD and TSS at the effluent). This effect was produced by the abundant presence of *S.natans*, which extend from flocs into the bulk solution and interfere with compaction, settling, and thickening processes of activated sludge. Class 13 corresponds to days with settling dysfunctions caused by the growth of *Nocardia* spp. or *Microthrix Parvicella* or type 1863 (organisms with hydrophobic cell surfaces). These organisms form air bubble-floc aggregates less dense than water that float to the aeration tank surface to form greasy thick brown foam. Four different sub-states were characterised according to the biomass state and the degree of affectation of the effluent. Class 12 is a situation that combines foaming of *Nocardia* spp. (organism with hydrophobic cell surfaces) and filamentous bulking caused by *S.natans* and *Haliscomenobacter*. Some global variables (*i.e.* F/M and SRT) are necessary to characterise these situations.

Codification step. All the knowledge and information acquired in the previous steps must be finally codified by means of heuristic rules. These rules, which are specific to the WWTP, replace or complement general inference paths in the decision trees of the KB, once validated by the expert. The objective of this step is to reduce the number of essential nodes and variables that must be evaluated to reach the final conclusion.

IF	$COD_{Effluent} > 160$ g/m^3 and/or $TSS_{Effluent} > 40$ g/m^3 and SVI = Normal or Low and (Diversity of ciliates < 0.5 or Dominant protozoa key group ='*Opercularia* and *Gimnamoebae*')	THEN	Deflocculation = True

Table 10 Specific rule resulting from class #9.

For instance, class #9 (interpreted as deflocculation) was well characterised by a) a cloudy effluent (high values of COD and/or TSS at the effluent), b) a normal or low value of SVI, and c) low diversity of ciliates or *Opercularia* and *Gimnamebae* as the predominant key group of the mixed liquor microfauna. In contrast, to reach the same diagnosis using the general decision tree it was not only necessary to have turbidity in effluent and the value of the sludge volume index, but it was also required information about the presence of bubbles and turbidity in the settling test analysis, and the floc morphology (see figure for deflocculation diagnosis in the appendix). Following this example, Table 10 shows the specific rule that can replace the general dec ision tree in the KB to diagnose deflocculation problems in the studied WWTP.

This methodology can be generalised to acquire specific knowledge from any (bio)chemical process, improving the development process and the efficiency of the expert system.

In [Comas *et al*., 1999], the results of the classification of only quantitative data versus the classification of the whole data (quantitative and qualitative data) of the Lloret WWTP database have been compared using two different automatic classification tools (Linneo$^+$ and AutoClass [Stutz and Cheeseman, 1995], see appendix for details about AutoClass). This comparison showed that the introduction of qualitative descriptors (mainly features related to the microfauna and filamentous bacteria identification and count and characterisation of activated sludge floc) gives several advantages (also spotted in inductive learning). Among them: extraction of more knowledge and identification of more situations (better diagnosis) than classifications with only quantitative data; better understanding of each situation; understanding of the relationships between microorganism presence and WWTP problems; and identification of several state-transition conditions.

Benefits of using automatic knowledge acquisition

To summarise, this sub-section lists some of the benefits of using automatic knowledge acquisition in the knowledge acquisition process. When a new rule is extracted by automatic acquisition (either by Linneo$^+$, CN2 or C4.5) and validated by the expert, different possibilities arise:

a) it can reduce the number of essential nodes and variables that must be evaluated to reach the final conclusion in the paths of some decision trees (*e.g.*, the case of deflocculation previously mentioned).
b) the specific knowledge acquisition process also enables to discover new knowledge (both new situations and rules) that was not acquired from the literature because it is specific to the facility. For instance in the classification of Granollers WWTP, from the interpretation of values from class #10, which reflects the ammonia shock situation, the rule shown in Table 11 can be codified. This rule is a clear consequence of the experience acquired in the particular WWTP of this study.

IF	$COD\|_{Influent}$ < 800 g/m^3 and $NH_4^+\|_{Influent}$ > 130 g/m^3	THEN	Ammonia_Shock = True

Table 11 Specific diagnose rule for ammonia shock in the WWTP.

Other new situations discovered include Partial nitrification with nitrite accumulation (possible inhibition), and the combined *rising* and phosphorous removal and organic underloading with partial nitrification.

c) Some new rules discovered are implemented in the knowledge base due to its accuracy and understandability according to the expert criterion. Other rules may not be as easy to be understood by the expert, because the way in which they classify a problem's attributes and properties may not be in accordance with the way that he/she would do it. Sometimes, they can make the expert to not trust them. An example of rule induced with CN2 that has been implemented is the one that predicts Foaming due to *Microthrix Parvicella* with 100% of accuracy:

IF	$Flow\|_{Influent}$ < 11000 m^3/d and $Flow\|_{By\text{-}pass}$ > 1000 m^3/d and *Nocardia* < common and *M.Parvicella* > common	THEN	Foaming = true

Table 12 Induced rule for detection of Foaming by *Microthrix Parvicella.*

d) The confirmation of the great relevance of qualitative features since a predominance of the qualitative variables over the quantitative variables was clearly observed in the C4.5-induced decision trees, the CN2-induced rules, and labelling the classes in Linneo$^+$. This fact agrees with the idea that qualitative attributes, including microscopic examinations of microfauna and bacteria, are useful indicators of the global performance of the WWTP processes.

e) The Linneo$^+$ has still an additional advantage relative to the common way to acquire specific knowledge of the process to build the KB: the increase in the understanding of some cause-effect relationships between presence of microorganisms and operational problems in the WWTP. Table 13 gives some examples of specific rules based on good qualitative-operational parameters correlations found in this study. These rules, only hinted in the literature, can be used as meta rules to conduct the reasoning throughout the KB.

IF	Microfauna abundance = 'High'	THEN	BOD and TSS at the effluent = 'Low values' (good quality of effluent)
IF	Dominant protozoa = 'Sessile/crawling ciliates'	THEN	BOD and TSS at the effluent = 'Low values' (good quality of effluent)
IF	Microfauna abundance = 'Low' and Dominant protozoa = 'Small Flagellates'	THEN	BOD and TSS at the effluent = 'High values' (bad quality of effluent)
IF	Settling test observations = 'Good settling' and Microfauna abundance = 'High'	THEN	Floc characterisation = 'Well-formed flocs'

Table 13 Correlations found in the classification process between some parameters.

f) Finally, the specific knowledge acquisition process can also help in the adjustment process of the boundaries among the different modalities of each quantitative variable considered in the KB. Note that the set of conditions of the heuristic rules can be based on modalities, being necessary to determine when the value of a quantitative variable (*e.g.* COD at the influent) is low, normal or high, and to register any qualitative observations (*e.g.* microorganisms presence) as few, regular or abundant. For example, in the general diagnosis path of filamentous bulking:

IF [SVI is High and Filamentous_Presence = high] THEN Bulking = True

the limit between normal and high modalities of SVI and Filamentous_Presence can be set by the values given by the centre of the filamentous bulking class of Linneo$^+$, or by the CN2 induced rule or C4.5 induced tree stating bulking.

5.3 Summary

The knowledge acquisition process for the KB development of an ES to integrate into the Activated Sludge Supervisory System has been described. As pointed out along this chapter, the use of expert systems presents a set of advantages that overcome the limitations of other techniques. Among them: ES facilitate the inclusion and retention of heuristic knowledge from experts and allow qualitative information processing; knowledge is represented in an easily understable form (rules); a well-validated ES offers potentially optimal answers because action plans are systematised for each problematic situation; besides, ES enable acquisition of a large general knowledge base, with flexible use for any WWTP management. Finally, ES allow an objective acquisition of specific knowledge throughout the use of machine learning techniques.

Simultaneously, expert systems also show some limitations: most of the knowledge acquired is general knowledge to manage any WWTP (coming from literature revision), with which there is a lack of specificity, mainly in the repertory actions proposed. Besides, the few specific knowledge extracted comes from difficult interviews with plant managers and workers (bias, discrepancies and imprecision) and of the database study and classification, often incomplete and almost never contain qualitative information. People tend to remember their past endeavours as being successful, regardless of whether they actually were or not. Complex problems require many (hundreds of) rules, causing long development time and may create problems in both using the system and maintaining it. And maybe, the most important, the knowledge base is static. Once developed, it is not an easy task, at least for the expert or final user, neither to modify some rules nor to adapt the knowledge base to new specifications and the system is unable to learn from new experiences. This last fact could provoke the systematic repetition of errors in diagnosis and proposed actions. All these limitations indicate that ES should be complemented with other approximations to manage complex processes optimally. Our next approach was to study the integration of a Case-Based System to the overall supervisory system to co-operate with the ES and numerical control.

6 CASE-BASED SYSTEM DEVELOPMENT

6.1 Introduction

This chapter details the development of the case-based system (CBS) module for its implementation in the Supervisory System of the wastewater treatment plant of Granollers. The methodology proposed permits the use of past experiences to solve new problems that arise in the process. It is based on the idea that the second time we solve a problem it is usually easier than the first time because we remember and repeat the previous solution or recall our mistakes and try to avoid them. The basic idea is to adapt solutions that were used to solve previous particular problems that have affected the process performance and use them for solving new similar problems with less effort than with other methods that start from scratch to build up new solutions. CBSs have been used recently in supervision, medical detection, planning, design and alternative selection, due to their good performance and relatively easy development. In a Case-Based System the information of these experiences is stored as a set of cases.

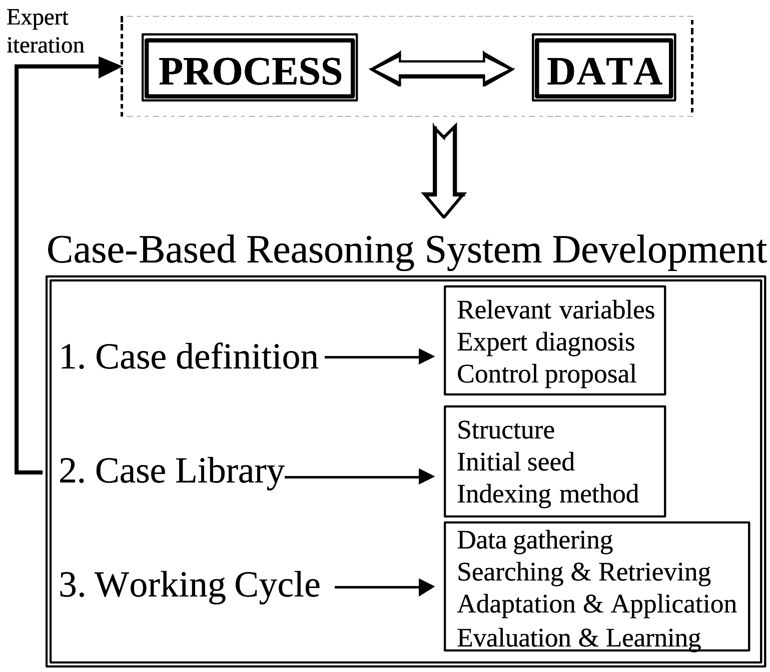

Figure 22 Flow diagram of case-based system development.

A case is described as a conceptualised piece of knowledge representing an experience that teaches a fundamental lesson to achieve the goals of the reasoner [Kolodner, 1993]. In our approach, each case is composed of a situation of the WWTP, the corresponding set of observations related to that situation and the control proposal carried out. These observations are the most relevant variables of the wastewater system studied. The set of specific cases is stored in a structured memory in a case-base (the case-library) and initialised with a set of typical cases of the plant. The CBS development includes the case and the case-library definition, and the selection of the initial seed. At the end of this chapter, we outline how the CBS works as a cycle. The

CBS cycle includes the data gathering, search and retrieval process, the adaptation and application, the evaluation and the learning steps. Figure 22 shows the three key building blocks of a CBS.

6.2 Case Definition

In the case-based developed system each case reflects a 24 h-characterised situation in the wastewater treatment plant. The information of each situation is codified in a storable and easily retrievable form for future use. Each case is defined by the following attributes. In Figure 23 it is shown each one of the attributes defining a particular and real case stored in the Granollers WWTP case-library.

- An **identifier** or label: In this study, we have used the date of the day preceded by "Case-" (*e.g.*, Case-DD-MM-YYYY).
- The **description of the situation**, which is based on the values of a set of observations (**relevant variables**) that define the case. Among all the available measures (either signals and off-line values), we only kept those that were relevant to the experts, this is, variables that can clearly describe each situation and distinguish it from another according to expert criteria. Selected variables represent the use of the expert preferences in the decision making process. Selection of variables to characterise the Granollers WWTP was done together with the manager of the plant, and was based on both statistical criteria and manager's experience. After this selection, nineteen out of the 74 variables listed in tables 4.2 and 4.3 were considered as the key elements that clearly identify a particular situation in the plant. These variables were:
    - the influent flow rate (Flow-I)
    - the concentrations of organic matter (measured as chemical oxygen demand, COD) and suspended solids (SS) in the influent (I)
    - the concentrations of organic matter (COD) and suspended solids (SS) in the primary effluent (P)
    - the concentrations of organic matter (COD) and suspended solids (SS) in the effluent (E)
    - the concentration of total kjeldhal nitrogen (TKN) in the influent (I)
    - the concentration of total nitrogen (TN) at the effluent (E)
    - the concentration of biomass in the aeration tank (MLSS-AS)
    - the settleability index of activated sludge (Sludge Volume Index, SVI)
    - the wasting (WAS) and recycle activated sludge rate (RAS)
    - the dissolved oxygen concentration of the first aerobic zone in each line (DO1 and DO2)
    - the sludge residence time (SRT)
    - the food to microorganism (F/M) ratio and
    - the predominant filamentous organism (*Filam*)
    - observations in the V30-settling test (V30-settling test)
- The **expert diagnosis**, which is implicit to each case and indicates the expert evaluation of the "state" of the process. Examples of diagnoses can be: suspended solids or organic matter shock, poor sludge sedimentability, storms, denitrification in secondary clarifiers (*rising*), etc…

- The suggested control or **recommended actions** to keep the process under control. These actions are meant to either maintain or switch the plant to normal operation conditions. The actions may be punctual (*e.g.*, a change of the dissolved oxygen set point in the bioreactors, an increase of the recycle sludge rate, etc.) or they may contain a subset of actions if it is a complex problem.
- The **evaluation** of the results obtained after applying the recommended actions on the plant. Both success and failure of the actions are recorded.
- A **utility measure**, that computes the ability of the case in solving past cases. This value is commuted from the previous experience in the application of the proposed action and is updated for all cases in the library at the end of each supervisory cycle to reflect which cases were useful in that cycle ([Sànchez-Marrè *et al.*, 1997a] give more details about this factor).
- The **similarity** or distance between a given case and previous ones, which are stored in the case-library (measures the closeness between the retrieved case from the library and the current case).

:identifier	((	Case-30-11-99		))
:description of the situation	((	Influent flow rate (Flow-I)	20023	)
	(	Influent-COD (COD-I)	830	)
	(	Influent-Suspended Solids (SS-I)	272	)
	(	Influent-Total kjeldhal Nitrogen (TKN-I)	136	)
	(	Primary effluent-COD (COD-P)	652	)
	(	Primary effluent-SS (COD-P)	130	)
	(	Primary effluent-COD (COD-E)	96	)
	(	Effluent-Suspended Solids (SS-E)	22	)
	(	Effluent-Total Nitrogen (TN-E)	96	)
	(	Biomass Concentration (MLSS-AS)	3113	)
	(	Sludge Volumetric Index (SVI-AS)	169	)
	(	Waste Activated sludge Rate (WAS)	36	)
	(	Recycle Activated sludge Rate (RAS)	1036	)
	(	Dissolved Oxygen_line1 (DO1)	2.9	)
	(	Dissolved Oxygen_line2 (DO2)	2.7	)
	(	Sludge Residence Time (SRT)	Attached ciliates	)
	(	Food to Microorganism ratio (F/M)	Abundant	)
	(	Filamentous_organism_Predominant (*Filam*)	*Microthrix*	)
	(	V30-setttling test observations (V30-settling test)	Good but foams on supernatant	))
:diagnosis		*Foaming* caused by *Microthrix Parvicella*		
:actions	((	1. Cause Identification: Low F/M ratio		)
	(	2. Physical aeration tank foam and clarifier foam removal		)
	(	3. High wasting activated sludge flow rate		)
	(	4. Minimum Recycle activated sludge flow rate to facilitate good compactation		)
	(	Check also for *Nocardia* trends during a week		))
:evaluation	((	Success. In five days, *Nocardia* population starts to decrease		))
:utility measure	((	0.76		))
:similarity	((	94.1 %		))

Figure 23 Example of a real case stored in the case-library.

6.3 Case-library

A CBS requires a database (known as case-library), which stores an array of relevant cases that roughly covers the problems that may arise in the plant. The organisation of the case-library is different from a common database in which a complete match among variables is required. In the case-library, cases are indexed so that the most similar case can be retrieved. In a CBS, the structure and the organisation of the library is crucial because it has an effect on both the system's response time and its success in finding a suitable stored case to solve the actual situation.

6.3.1 Structure

The case retrieval task is strongly dependent on the case-library organisation or structure. Most common case-library structures in CBS can be classified based on two general approaches: flat memories and hierarchical memories (using prioritised discrimination networks/trees).

Flat memories consist simply of a database with historical cases. Flat memories have the advantage that always retrieves the set of cases with the best match with the actual case. Moreover, adding new cases to the library is cheap. On the other hand, they have a major disadvantage: the retrieval time is very time-consuming (and so, expensive) since every case in the memory is matched against the current case, using a Nearest Neighbour (NN) algorithm [Dasarathy, 1990].

In contrast with the **hierarchical memories**, the matching process and retrieval time are more efficient because, after a prior discriminating search in the hierarchical structure, only few cases are considered for similarity assessment purposes. However, they also have some disadvantages: the hierarchical structure maintenance in an optimal condition requires an overhead on the case-library organisation, and the retrieval process could miss some optimal cases if it searches in the wrong area of the hierarchical memory. This problem becomes especially critical in prioritised discrimination networks/trees.

<table>
<tr><th rowspan="2">Attribute</th><th rowspan="2">Order</th><th rowspan="2">Weight</th><th colspan="5">Modalities</th></tr>
<tr><th>Low (L)</th><th colspan="2">Normal (N)</th><th colspan="2">High (H)</th></tr>
<tr><td>Influent flow rate (Flow-I)</td><td>6</td><td>6</td><td>(< 19000)</td><td colspan="2">(19000 - 24000)</td><td colspan="2">(24000 - 60000)</td></tr>
<tr><td>Influent-COD (COD-I)</td><td>4</td><td>8</td><td>(< 650)</td><td colspan="2">(650 - 850)</td><td colspan="2">(850 - 2850)</td></tr>
<tr><td>Influent-SS (SS-I)</td><td>5</td><td>7</td><td>(< 230)</td><td colspan="2">(230 - 330)</td><td colspan="2">(330 - 750)</td></tr>
<tr><td>Influent-TKN (TKN-I)</td><td>8</td><td>9</td><td>(< 60)</td><td colspan="2">(60 - 90)</td><td colspan="2">(90 - 200)</td></tr>
<tr><td>Primary effluent-COD (COD-P)</td><td>-</td><td>9</td><td>(< 525)</td><td colspan="2">(525 - 720)</td><td colspan="2">(720 - 1500)</td></tr>
<tr><td>Primary effluent-SS (SS-P)</td><td>-</td><td>7</td><td>(< 40)</td><td colspan="2">(40 - 120)</td><td colspan="2">(120 - 500)</td></tr>
<tr><td>Effluent-COD (COD-E)</td><td>3</td><td>8</td><td>(< 110)</td><td colspan="2">(110 - 140)</td><td colspan="2">(140 - 465)</td></tr>
<tr><td>Effluent-SS (SS-E)</td><td>1</td><td>8</td><td>(< 10)</td><td colspan="2">(10 - 20)</td><td colspan="2">(20 - 95)</td></tr>
<tr><td>Effluent-TN (TN-E)</td><td>9</td><td>9</td><td>(< 60)</td><td colspan="2">(60 - 90)</td><td colspan="2">(90 - 200)</td></tr>
<tr><td>Biomass Concentration (MLSS-AS)</td><td>7</td><td>7</td><td>(< 1000)</td><td colspan="2">(1000 - 2000)</td><td colspan="2">(2000 - 4000)</td></tr>
<tr><td>Sludge Volumetric Index (SVI)</td><td>2</td><td>8</td><td>(< 50)</td><td colspan="2">(50 - 100)</td><td colspan="2">(100 > 1000)</td></tr>
<tr><td>Sludge Residence Time (SRT)</td><td>-</td><td>7</td><td>(< 5)</td><td colspan="2">(5 – 8)</td><td colspan="2">(8 – 15)</td></tr>
<tr><td>Food to Microorganism (F/M) ratio</td><td>-</td><td>8</td><td>(0 – 0.25)</td><td colspan="2">(0.25 – 0.35)</td><td colspan="2">(0.35 - 1.5)</td></tr>
<tr><td>Filamentous organism predominant (Filam)</td><td>-</td><td>8</td><td>Zooglea</td><td>Microthrix</td><td>021/thiotrix</td><td>Nocardia</td><td>None</td></tr>
</table>

Table 14 Order, weight and modalities for the relevant variables defining a case in Granollers

In this study, the case-library can be organised either as a plain memory or as a hierarchical memory using a lazy prioritised discrimination tree (see Figure 24 and [Sànchez-Marrè *et al.*, 1997a]), where each branch or node corresponds to the evaluation of a variable, and terminal nodes contain the stored cases. Plain memory was used at the beginning of the prototype implementation since the case-library was not very large yet (until about 100 cases). As the number of cases increased, a prioritised tree was used to reduce the retrieval phase.

To build the prioritised discrimination tree, each defining variable was divided into several qualitative categories (*e.g.* high, normal or low), and, after an iterative process together with the plant manager, a weight and a discriminant order was assigned to each variable to steer the search order. The weight and discriminant order of each variable should illustrate its relevance in the characterisation of the state of the plant. This is a key step because it enables the organisation of the case-library into the hierarchical tree, which optimises the retrieval phase. If the prioritisation process is not correct, access time will be lengthened as the sequence of search will not be efficient enough and it may affect also the quality of the retrieved cases. Table 14 shows the order, weight and qualitative modalities for each variable. As shown in Table 14 for the Granollers hierarchical tree, sometimes not all the variables are selected to build the tree, in that case, it is not necessary to assign them the priorisation order.

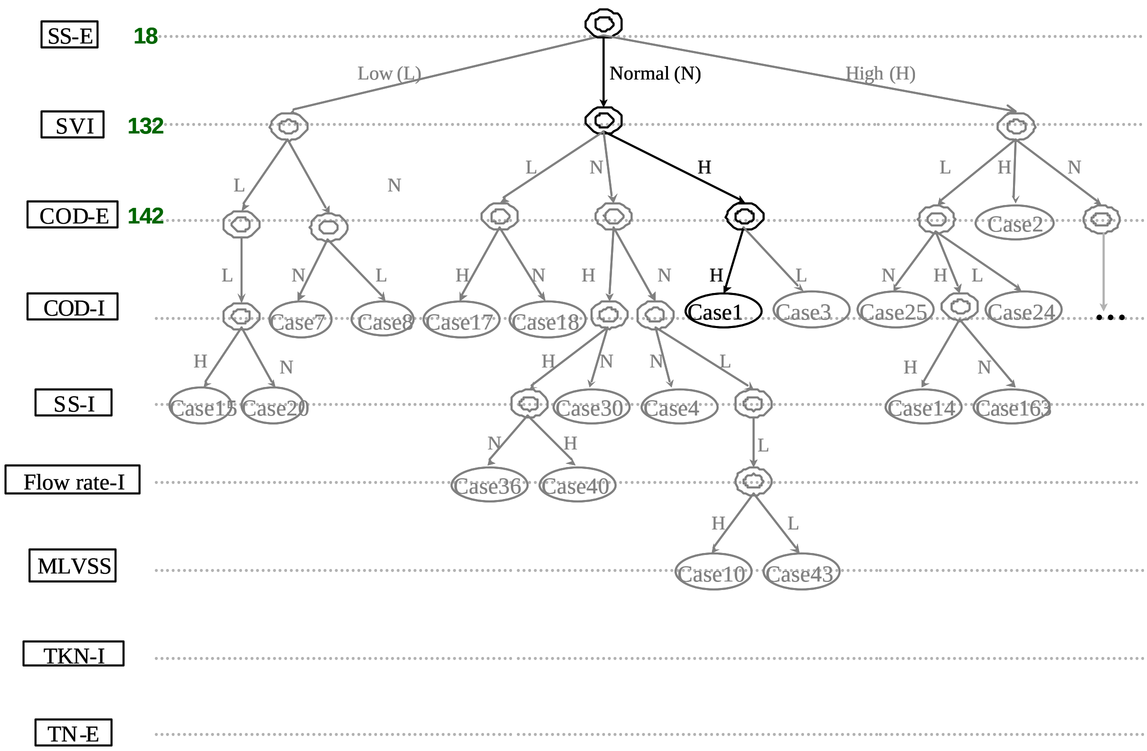

Figure 24 Example of a hierarchical case-library with the most similar case retrieved

After the relevant variables are discretised and prioritised, the library is ready to be built. A set of initial cases is necessary for this purpose (initial seed). The case-library building begins evaluating the variable considered for each node (as specified by the prioritised order) for the two first cases. The value of the variable is enquired qualitatively generating the corresponding branches. With the hierarchical structure, the case-library has at each node as many branches as different discretised values are defined for the attribute. This is done according to the corresponding values of the attributes considered. The variables are evaluated until the two cases are differentiated or, if not, all variables are evaluated and the two cases are stored together at a final leaf. This process is repeated until all the considered cases appear as a final element. When the CBS is performing and a new case is retrieved, the searching process follows the same progression: the qualitative value of the variable is evaluated at each node arriving at a leaf occupied by a stored case. The hierarchical structure of the CBS module supports missing information since a frequency value is associated to each branch of the tree.

6.3.2 Initial Seed

First of all, the range of cases to be covered in the initial seed must be defined according to the typical situations occurred in the plant studied, including normal operation and abnormal process conditions caused either by operational problems, mechanical faults or anomalous influent characteristics. These specific cases can be obtained from the historical database from existing reports of the plant and interviews with the plant manager. An automatic data classification method (*e.g.*, Linneo$^+$, see section 5.2.3.2) can be used for selecting some typical or common situations from the historical database. As the historical data are often not complete enough to generate robust cases (*i.e.*, rarely all relevant observations are listed), interviews with process experts enables to rely on their own experience to add other essential information (*e.g.*, specific action proposed in front of a certain situation). After this step, it is recommended to upgrade the library with other common situations (or general cases) obtained from technical books, troubleshooting guides or provided by general process experts. This group of cases collected represents the initial seed of the case-library.

Once the initial seed is defined, the CBS is ready to propose adequate solutions to detected problems similar to those archived in the initial "seed". Otherwise, the CBS would have to learn a significant number of actual process cases before it can be useful, lengthening the *set up time* before the CBS could be used successfully. The library of Granollers WWTP was initialised on August 1999 with a representative set of 74 real cases from the historical database, which covered a broad range of main problems of the process and normal situations (Table 15).

Situations Covered by the Initial Seed	Number of Cases
Normal	44
High influent organic nitrogen conc.	2
Toxic shock (low COD removal efficiency)/Deflocculation	1
Filamentous bulking	2
Nitrification and Phosphorous removal	2
Underloading	3
Nitrification	6
Hydraulic overloading	2
Overloading	4
High influent ammonia nitrogen conc.	1
Foaming (*Microthrix Parvicella*)	2
Foaming (*Nocardia*)	2
Electric power cut affecting the biomass quality	2
Beginning of filamentous bulking	1

Table 15 Situations considered in the initial seed of the CBS of the Granollers WWTP

Long-term success of the case-library demands its continuous evolving by addition of new cases, refinement of existing ones and forgetting the useless ones. The library keeps being updated with new cases as knowledge about the process grows; so, the CBS evolves into a better reasoner system and thus, system accuracy improves. From the beginning of the CBS implementation and during the five-month field validation phase, the case-library has increased with more than 100 complete new cases with diagnosis and action plan carried out registered. Thus, in March 2000 the CBS stored about 200 relevant experiences acquired from the plant operation, part of them related to situations already covered and part related to new situations. The new situations learnt during these period include beginning of foaming, storms, high influent flow rates variations, aeration problems, deflocculation (disperse growth), combination of the previous. To avoid overwhelming the library with large amount of information, it is crucial to only include the most relevant cases. This relevance criterion is determined by the expert and refers to the required degree of similarity between two cases to be considered equivalents.

6.4 The Working Cycle

Once the case-library is built (*i.e.*, relevant variables selected and discretised and weight assigned for plain memory; moreover, priority order is assigned for hierarchical structure), the CBS reasoning tasks begin when a new case arises. The CBS performs with a cyclic process (Figure 25). This cyclic process carries out several tasks concerning the following steps:

6.4.1 Data gathering and processing

To define the current case, the required data is gathered from the database. According to the values of each of the 19 selected variables, the weight of each variable of the current case is modified or not. If a variable has an outlier value (high or low), its relevance into the description of the situation must be higher than if it has a normal value (*i.e.*, the weight changes according to the value of the variable). For example:

IF the Inflow-rate < 12500 m^3/d or the Influent-flow rate > 26000 m^3/d THEN
conclude that the Influent-flow rate-weight = 10 ELSE
conclude that the Influent-flow rate-weight = 6

Thus, the importance of the variables (expressed as the weight) is amended according to its value. In addition, if the actual value of any variable is missing, a value of 0 is assigned to its weight. This means that this variable will not be considered in calculating the similarity distance. Nevertheless, the assigned weights as well as the minimum and maximum values of each variable can be modified interactively through the interface. Modifications can be either suggested by the expert criteria or by some of the CBS validation procedures carried out.

6.4.2 Case Retrieving

This phase consists of exploring the case-library to find the historical case (or cases) that closely resembles the current problem. The cases that best match the actual problem are retrieved based on an algorithm that compares and numerically ranks the cases. Two possible searches can be done:

- If we use a case-library with flat memory, the search is carried out through all the available cases in the library

- Otherwise, if we use a hierarchical case-library, only some branches of the discriminant tree will be explored. This discriminant process is based on an algorithm to search for similar cases by moving along the case-library tree. The algorithm evaluates the corresponding variable at each node following the order established in Table 14. This process is done by discretising the variables of the new case and using the corresponding qualitative comparison criteria. The selection of the first and second best case at each node lead to a set of cases that closely resembles the case under study. See reference ([R.-Roda *et al.*, 2000b] and [Sànchez-Marrè *et al.*, 1997a]) for more details about the searching algorithm.

When the stored cases are retrieved, the comparison task to find the most similar cases consists of matching the attributes of the current problem with those of each historical case retrieved, and computing for each case a composite similarity metric. When working with flat memory, the system retrieves the three most similar cases while in hierarchical memory, the number of cases retrieved depends on the branches explored.

In the two memory approaches, selection of the best case available from the retrieved cases is based on a quantitative similarity criterion. In the present work, two different weight-sensitive similarity criterions were applied: the distance called *L'Eixample* [Sànchez-Marrè *et al.*, 1998], which is a normalised exponential weight-sensitive distance function, and a generalised weighted-distance function (typical Hamming distance):

- a generalised weighted-distance function (Manhattan criteria) is:

$$d(x,y) = \frac{\sqrt{\sum_{i=1}^{n} w_i \times diff(x_i, y_i)^2}}{\sqrt{\text{number of variables } i \text{ for which both } x_i \text{ and } y_i \text{ are known}}}$$

where $diff(x_i,y_i) = 0$ if either x_i or y_i are unknown and $diff(x_i,y_i) = difference(x_i,y_i)$ otherwise.

- a normalised exponential weight-sensitive distance function (called the *Eixample* distance), which is defined by the following equation:

$$d(C_i, C_j) = \frac{\sum_{k=1}^{n} e^{w_k} \times d(A_{ki}, A_{kj})}{\sum_{k=1}^{n} e^{w_k}}$$

where

$$d(A_{ki}, A_{kj}) = \begin{cases} \frac{|\, quantval(A_{ki}) - quantval(A_{kj}) \,|}{upperval(A_k) - lowerval(A_k)} & \text{if } A_k \text{ is an ordered attribute and } w_k \le a \\ \frac{|\, qualval(A_{ki}) - qualval(A_{kj}) \,|}{\#\mathrm{mod}(A_k) - 1} & \text{if } A_k \text{ is an ordered attribute and } w_k > a \\ 1 - d_{qualval(A_{ki}), qualval(A_{kj})} & \text{if } A_k \text{ is a non-ordered attribute} \end{cases}$$

and,

C_i is the case i; C_j is the case j; W_k is the weight of variable k; A_{ki} is the value of the variable k in the case i; A_{kj} is the value of the variable k in the case j; qtv(A_{ki}) is the quantitative value of A_{ki}; qtv(A_{kj}) is the quantitative value of A_{kj}; A_k is the variable k; upperval(A_k) is the upper quantitative value of A_k; lowerval(A_k) is the lower quantitative value of A_k; α is a cut point on the weight of the variables; qlv(A_{ki}) is the qualitative value of A_{ki}; qlv(A_{kj}) is the qualitative value of A_{kj}; #mod(A_k) is the number of modalities (categories) of A_k; δqlv(A_{ki}),qlv(A_{kj}) is the δ of Kronecker.

The *Eixample* distance accounts for the different nature of the quantitative and qualitative values of the variables. Also, the distance function is weight sensitive in the sense that for the most relevant variables, the distance is computed based on their qualitative values (thus maintaining or amplifying the differences between cases). For the less relevant variables, the distance is computed based on their quantitative value reducing the differences between cases. Alfa (α) is the cut point that fixes whether the distance is computed on their quantitative or qualitative values (depending on the weight of the variables). When the distance between the most similar case and the new one is too large (the expert defines a border between similar and new cases, the parameter beta - β -), the CBS considers the actual case as a new experience.

Both distances require are weight-sensitive, therefore, a weight must be assigned to each variable that defines the case before calculating any distance (see Table 14). The weight assignment is based on expert criteria and the weights are adjusted in the CBS partial validation phase.

6.4.3 Case Re-Use, Adaptation and Application

If the most similar case stored is significantly different from the current problem, an adaptation of the solution of the retrieved case may be required to re-use it. In our approach, we propose just a linear interpolation adjustment of the parameters involved in the control strategy to adapt the retrieved solution when the retrieved case does not perfectly match the current case. Although a linear interpolation is a simplification of the real world, this assumption can be reasonable when the behaviour of the process is far from highly non-linearity. In the case of the WWTPs, although the system is non-linear (as is well recognised in the mathematical models used to describe the process), some perturbations have such long delays that our assumption can be acceptable.

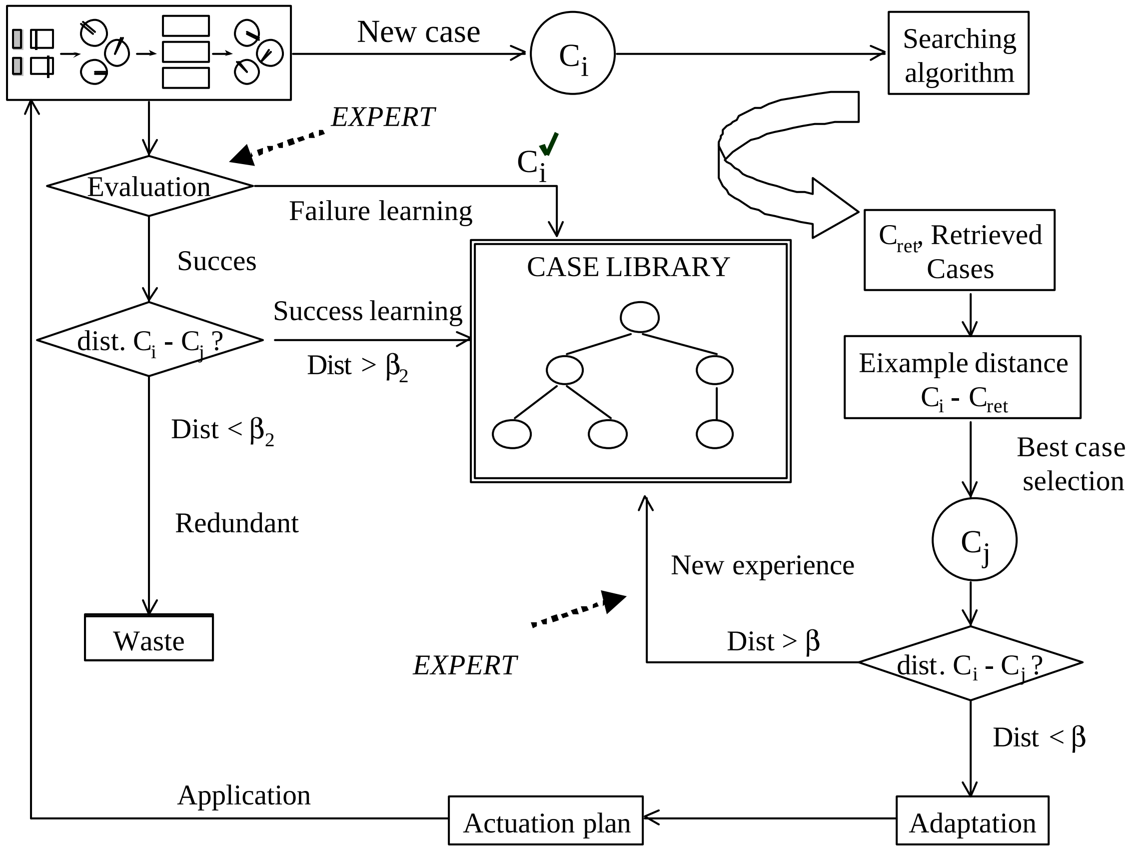

Figure 25 Case-based system cycle.

As stated before, there are few control parameters that can be modified in a facility, mainly recycle and wasting sludge flow rates, dissolved oxygen set-points, and chemical additions in case the treatment involves chemical treatment. The actions to be taken require **"to maintain"**, "**to reject**", "**to increase**" or "**to decrease**", and the adjustment involves a slight modification of the parameters. Even if the similarity distance is small enough, no adaptation of the solution is required. For example, in two similar situations of “low oxygen level in the bioreactor”, the proposed action plan is identical: “raise the aeration of the bioreactor” and its application modifies the value of a parameter that, in this case, is the airflow rate.

If the actual case is considered as a new case with no enough similar cases in the case-library (computed similarity distance to any case is greater than the parameter β), then, to deal with this situation, it is necessary to consider other techniques that are not based on stored experiences.

The whole information generated by the CBS is compiled and sent to the upper module for supervision with the Expert System conclusions. Nevertheless, if the supervisory module selects the experiential solution based on previous cases, before the application of the suggested action (or solution), a final evaluation or revision of the results is usually required to the human expert. There are different ways to evaluate these results: by direct expert or operator answering, by simulating the proposed actions and evaluating its consequences, by directly getting a feedback of the results of the proposed solution or by combination of the previous.

6.4.4 Case Learning

This phase is concerned with knowledge learning or retaining from each new experience to update the knowledge contained in the case-library to be useful for future problem solving. CBS can learn both from successful and from failures solutions. When a new case has been solved successfully, it should be incorporated to the library, so that the CBS can benefit from its information in the future situations. This is known as *learning from success*. Nevertheless, to avoid the introduction of redundant information, only cases that add some complementary knowledge should be incorporated. Thus, only new cases with distances to the most similar historical case greater than the parameter β_2 are kept. In the initial phase of a CBS implementation, it is interesting to diminish β_2 in order to force the system to learn almost all cases in order to increase significantly the case-library. Alternatively, if the proposed solution fails, it should also be recorded to prevent similar mistakes in the future. This is known as *learning from failure*. The human expert is who is in charge of evaluating the success or failure and recording the result of the action proposed by the retrieved case. The learning capability is one of the outstanding features of a CBS. Both learning strategies are graphically described in Figure 25. Extended details on the evolution of the CBS prototype to improve accuracy and speed of searches can be found on the following references: [Sànchez-Marrè *et al*., 2000] and [Sànchez-Marrè *et al*., 1999a].

6.5 Summary

Case-Based Systems offer a number of advantageous features that allow improvement of the management and control of complex systems like WWTP. These features have been highlighted along this chapter and can be resumed into: (1) most of the knowledge contained in the CBS is totally specific to the WWTP (*i.e.*, experiential knowledge based on historical information of the process itself) and, therefore, the proposed actions will have greater guarantees of success when confronting the different operational problems or cases occurred at the plant; (2) CBSs are more flexible than ES because exact matching is not required; (3) moreover, CBS are easier to develop (historical cases normally already exist as corporate documentation) and less expensive to maintain than ES, and more important (4), CBSs are dynamic systems with respect to the knowledge contained that enhance their behaviour with time since allow to implement learning tasks from new experiences, either from successful as well as from failed.

In spite of these evident advantages with respect to ES, CBSs also present some limitations: a CBS cannot cope with situations that have never happened before in the process because the case-library does not include reference cases to compare to it and the actual implementation is not suitable for making predictions. For this reason, it is recommended to complement CBS with ES and prediction models developed with mathematical algorithms or soft-computing techniques. Next chapter explain the integration of several classical and AI methods into an hybrid approach to optimise the WWTP management and control.

7 IMPLEMENTATION OF THE SUPERVISORY SYSTEM

7.1 EDSS Architecture

In this chapter, the implementation of our DAI approach is described in detail. Implementation, as pointed out by [Klein and Methlie, 1995], is the process of converting the initial conception of a knowledge-based system into a tool that could be effectively used. The expert participation in the system development effort is a key variable for a successful implementation.

According to the characteristics of the wastewater treatment process, the architecture of our computing approach was implemented as an **intelligent integrated supervisory system** structured into a **multi-layer** architecture. The existence of fixed abnormal situations such as storms, bulking, toxic loading, can be solved with a predetermined plan or strategy in a more efficient way using a supervisory system than using other types of DAI architectures such as blackboard systems or message passing.

Supervisory system: indicates that there is an upper level that centralises a control component that controls all reasoning of the system.

Multi-layer: The multi-layer architecture enables to deal with any kind of data gathered from the process (quantitative and qualitative), to include an array of different kinds of knowledge (numerical, heuristic, experiential, and predictive) and to supervise the different tasks of the system. Each kind of knowledge involves a different information technology (IT):

- classical control (numerical knowledge)
- Knowledge Based Systems: heuristics of the process codified as an Expert System (ES) and experiential knowledge of the specific plant represented as Case Based Systems (CBS)
- simulation models (numerical and predictive knowledge): mechanistic model and heterogeneous neural network model

Intelligent: The integration of these AI technologies provide the Supervisory System with an intelligent behaviour since it should be able to reason based on the heuristic knowledge from literature and experts (ES) and based on specific experiences accumulated through years of operation in the own facility (CBS). This is really essential for diagnosing and solving abnormal or problematic situations. The use of AI tools also enable the Supervisory System to make predictions with simulation models. This intelligent feature of the hybrid system allows to overcome the limitations of classical control in these kind of processes.

Integrated: This hybrid approach also tries to cope with the troubles of using a sole technique to solve real problems as the different intelligent technologies cooperate with each other, increasing machine-learning capabilities, improving reasoning capabilities (deeper knowledge) and upgrading decision making reliability.

This study proposes a Supervisory System applied to wastewater treatment plants, which integrate the capabilities of a KBS (can simulate reasoning and can explain their reasoning and conclusions) with the capabilities of classical DSS[5] (mechanistic model, data management, decision methodology, and to support decision making). Our approach takes advantage of the synergies of integrating KBS with traditional DSS focusing on quantitative mathematics and computational reasoning. As suggested by [Turban, 1992], if the results of the KBS and DSS could be reconciled and evaluated, the joint effort would probably produce better results than either approach independently.

In the previous chapters we have especially focused on the **development** of the different reasoning technologies. This chapter emphasises the **implementation** of the AI techniques individually, by the integration of the different tools into this multi-layer architecture and by the implementation of this architecture as a real time Supervisory System for the Granollers WWTP operation and control. The system developed for the Granollers WWTP has been named **BIOMASS**, that is, **B**esòs **I**ntelligent **O**peration and **M**anagement **A**ctivated **S**ludge **S**ystem.

Specifications of Implementation

The core and main modules of the intelligent integrated supervisory system, except CBS that has hierarchical memory, have been developed and are still currently implemented into the G2 object-oriented shell; a user-friendly development environment for creating intelligent, knowledge-based, real-time applications that already includes the inference engine [Gensym, 1997a]. G2 relieves the developers from low-level programming allowing them to move efficiently into the development of the engineering application.

Therefore, G2 sustains and controls the control algorithms that are not implemented in the PLCs network, on-line and off-line data acquisition, database management, temporal reasoning, the rule-based or expert system reasoning and the case-based system with plain memory. Moreover, G2 is able to scan the application, focusing on the relevant areas in the same way as a human expert would do, and provides easy connectivity with different data sources and other applications (SCADA and PLCs network - to acquire data and/or send an order to the on-line actuators -, and could be connected to case-based system with hierarchical architecture, mechanistic and neural network model…or any other external applications) with its G2 Standard Interface (GSI) capabilities [Gensym, 1995].

[5] A simulation model can be seen as a traditional decision support system.

Knowledge representation in G2 is maintained and extended through classes (in the *G2 class hierarchy*), rules of different types (*if, when, whenever, unconditionally, for, initially*), methods and procedures[6] (portions of code containing the details of how to perform any operation). Every class within the G2 class hierarchy is either a system-defined class or a user-defined class. G2 includes a large set of system-defined classes, many of which can be used as the foundation of customised, user-defined classes. Classes have attributes, which define the inherited and locally defined properties of the class.

Defining a hierarchy of objects and classes of objects saves time and space, as subclasses can inherit attributes from the class superior (above). An example of a class definition is the compartmentalised reactor of Granollers WWTP (see Figure 26). There are different types of reactors for the activated sludge process (type carrousel, SBR, complete-mixed, compartmentalised…). At the same time, the bioreactor can be activated sludge or fixed-film. All these types of equipments are used for the biological degradation of organic matter and/or nitrogen, and a superior class of bioreactor could be defined. Many attributes such as presence of foams on the surface, pH, V30, F:M…etc., are common to these objects, so they only need to be defined once in the superior class definition.

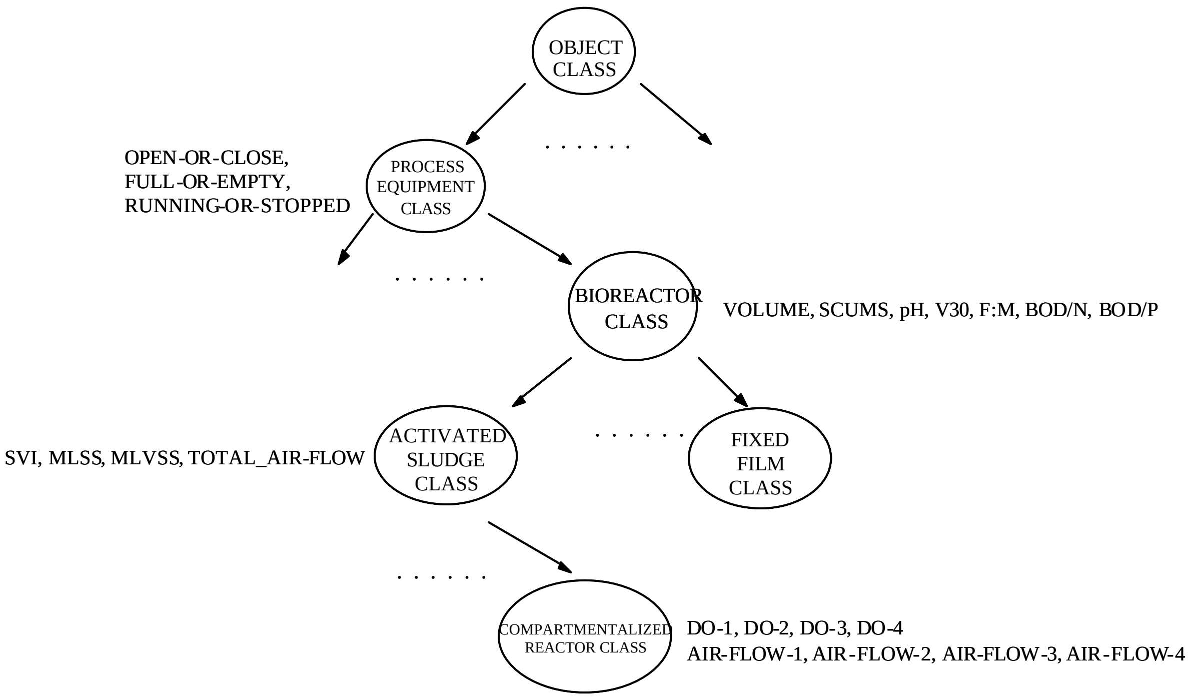

Figure 26 Definition of the Compartmentalised reactor class

As it is shown in Figure 26, the bioreactor class would have a superior class, for example, the process unit class, which would have a superior object class, that could be the highest level defined. This means that a few powerful generic rules can be written which apply to a wide range of objects avoiding duplication. In addition, new

[6] Methods are class-specific whereas procedures are not.

attributes can be added to any class if more aspects about the class are considered or otherwise they can be deleted. The Compartmentalised Reactor Class has 8 class specific attributes (the DO level and airflow at each compartment) and 14 inherited attributes (Open-or-Close, Full-or-Empty and Running-or-Stopped from the Process-Equipment Class, Volume, foams, pH, V30, F:M, BOD/N and BOD/P from the Bioreactor Class and SVI, MLSS, MLVSS and Total_Airflow from the Activated Sludge Class).

As shown in Figure 27, the most common units and objects present in WWTPs have been stored into the object base. Once the classes are defined different instances of them are created and connected between them to build the scheme of the WWTP. In the characterisation of the Granollers WWTP application, 679 object classes have been defined (323 user-defined and 356 system-defined). About 1004 attributes are defined as parameters or variables.

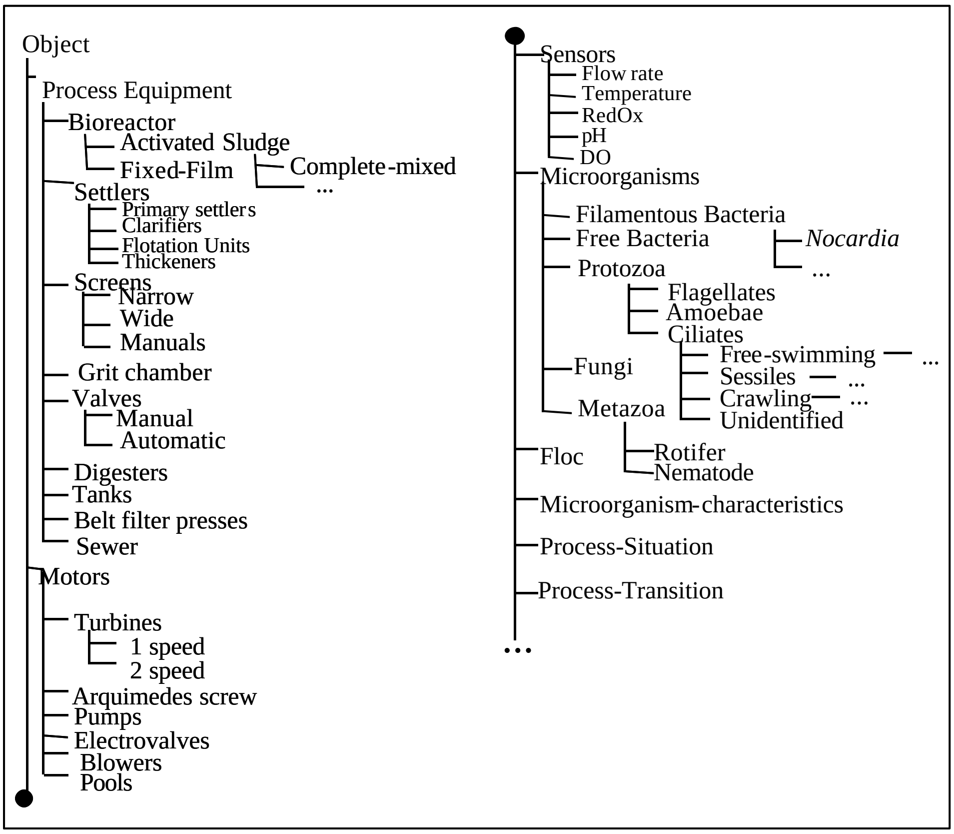

Figure 27 Part of the objects base of BIOMASS

Practically, the whole knowledge has been organised into G2-*Workspaces*. Figure 28 shows the main workspaces existing in the Granollers application: Knowledge (ES, CBS, supervision…), data, GSI, definitions, microbiological identification help module, and granollers-top-level (with plant diagrams, trend charts, numerical values of the modalities of variables…).

The chapter is organised as follows: it starts with a brief description of the multi-level architecture implemented; then, it continues with the description of the implementation of each knowledge modelling paradigm (numerical control, expert system, case-based system and simulation models); then, the multi-layer architecture is described in detail, focusing on the tasks carried out; and finally, details of the supervisory working cycle are given.

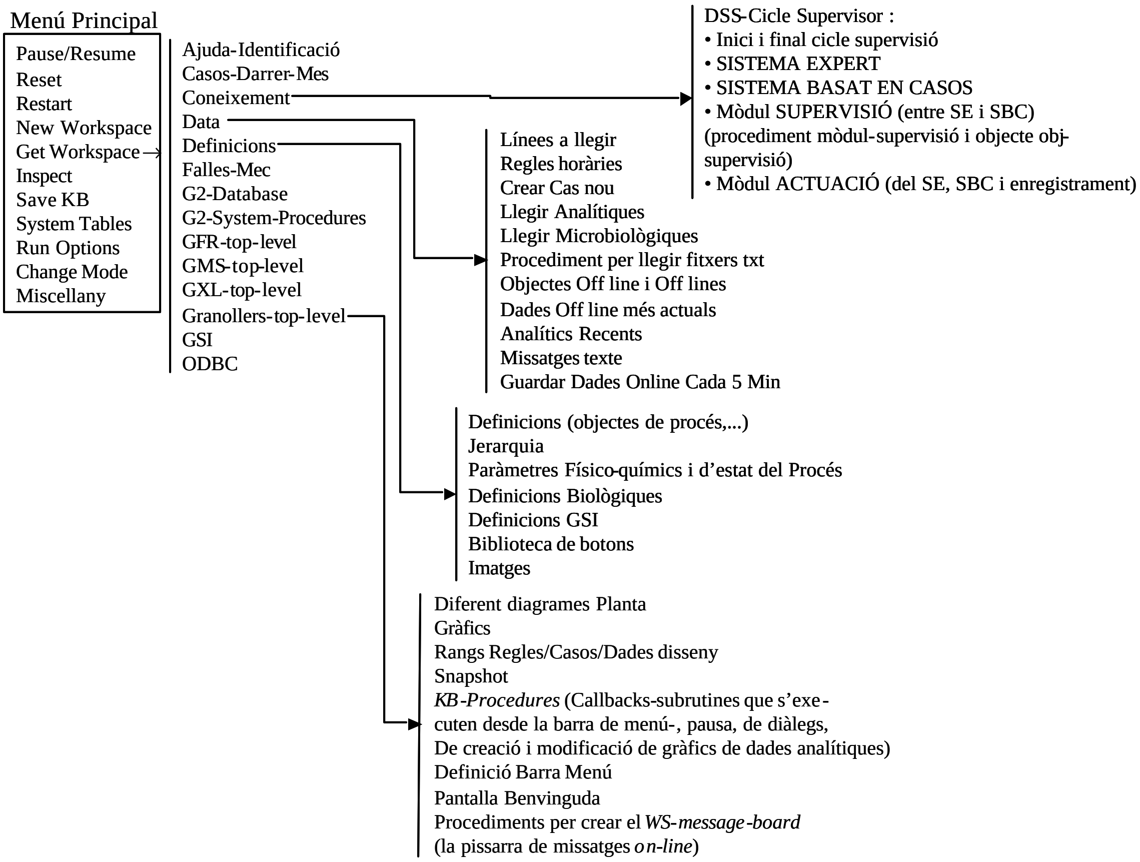

Figure 28 Scheme of G2-Workspaces existing in the Granollers application

7.2 The Multi Level-Architecture

The architecture of the Supervisory System provides an integrated framework for easy access to three layers or components: data analysis and interpretation (including database management); advanced tools of reasoning and integration (diagnosis module); and the decision support module (simulation models to implement a predictive or supervisory task over the plant). This multi-level architecture guarantees the useful and successful supervision of wastewater treatment processes. Figure 29 shows the structure of the computing approach to supervise the Granollers WWTP.

The first layer of the Supervisory System is the level that supports the data analysis and interpretation processes. This level is composed of the data acquisition process and data management from the temporal evolutive (real-time) database where on-line signals, coming from sensors and equipment, together with off-line biological, chemical and physical analyses of water and sludge quality, other qualitative observations of the process (*i.e.* presence of bubbles on settler surface…), and data calculated by the system are stored. Sometimes, a learning process takes place at this level either by evaluation of the CBS application (modification of case-library) or by knowledge acquisition from (new) experts or (new) knowledge sources, by means of automatic classification techniques. The second layer of this architecture includes two artificial intelligence techniques (expert system and case-based reasoning) and numeric models, overcoming the caveats and limitations in the use of each single technique, which constitutes the reasoning and integration module for situation assessment.

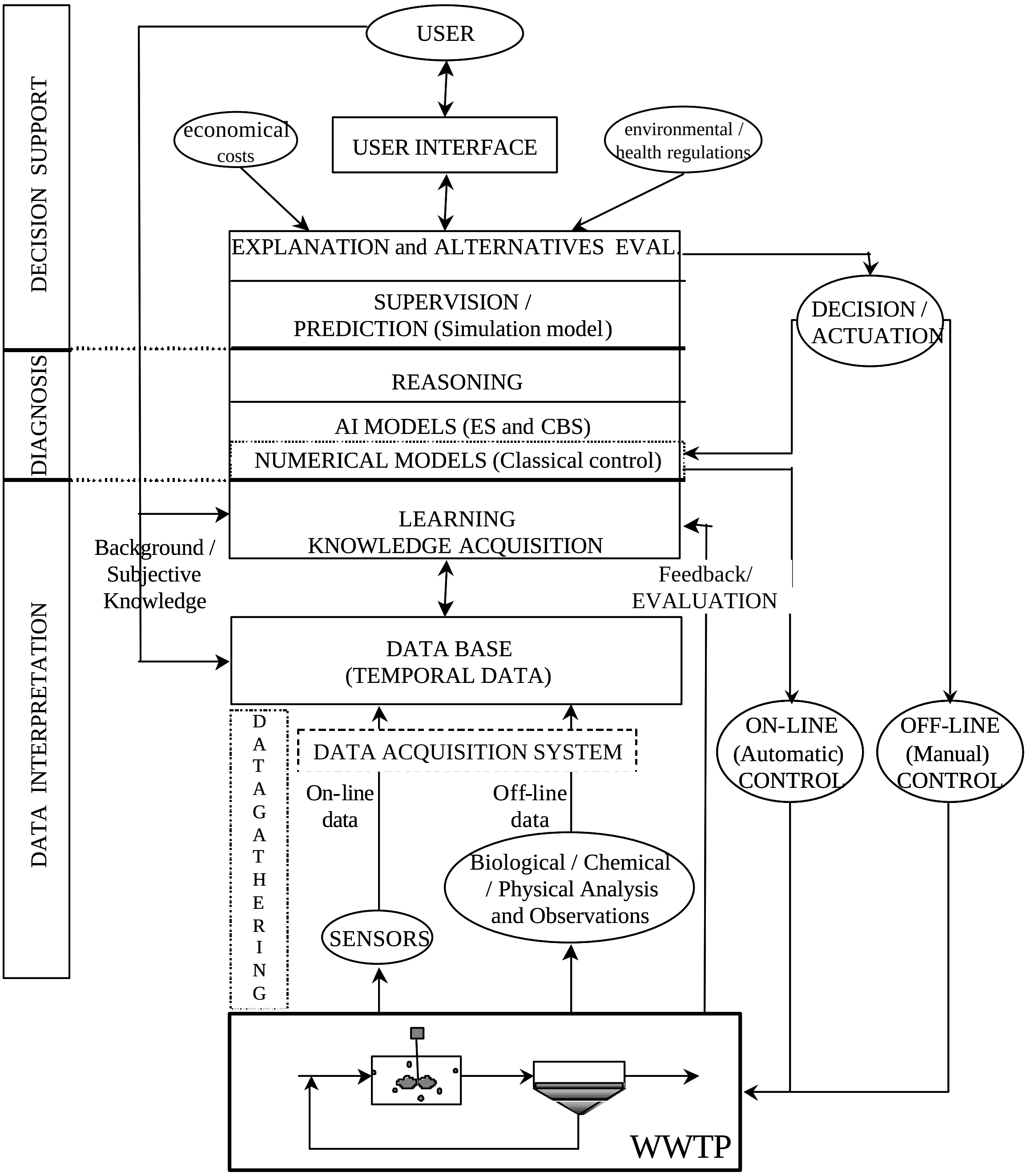

Figure 29 Integrated modules of the Computing Approach.

This second level entails cooperation between knowledge-based control and automatic control for the supervision of this complex process. This level implements the reasoning and integration tasks to diagnose its state and behaviour and to propose the action to maintain or re-drive the process to its normal operation. For each new supervisory cycle, the computer system activates the two knowledge-based systems for implementing reasoning tasks to diagnose the mechanical and operational state of the plant using the rule-based system and case-based system. Integration tasks are implemented in the rule-based system if contradictory results are suspected. In the CBS, if the retrieved cases are not similar enough, an adaptation to the current case will be necessary. The results of this operation are communicated to the third level.

The third (and upper) level of the Supervisory System (the decision support module) implements a supervisory and predictive task over the WWTP. The supervisory task of this module looks for the consensus on the diagnosis and actions proposed by the different reasoning tools. Meanwhile, the predictive task evaluates the possible alternatives of action by means of a dynamic model to predict the future behaviour of the plant and, finally, infers and suggests the most suitable action strategy to be considered. The decision-maker should consider the different alternatives in relation to socio-economic conditions and applicable legislative frameworks. This module also raises the interaction of the users with the computer system throughout an interactive and graphical user-machine interface (the user may query the system for justifications and explanations about suggested decisions, for consulting certain values…).

In the next sections, the implementation of each module is explained. Sections 7.3 to 7.7 refer to the implementation of classical control, expert system, case-based system, mechanistic model and black-box model. Later, in sections 7.8, 7.9 and 7.10, the three layers are extensively described. Finally, the performance of the Supervisory System as a cycle is illustrated.

7.3 Classical control

Classical control systems existing in the Granollers WWTP (DO controller and flow equalisation) together with the new control strategies on recycle, recirculation, and wasting rate already explained in the section 4.1.5 will be integrated within the architecture of the Supervisory System

Classical control systems based numerical algorithms are embedded in PLCs and regulated by the SCADA. This automatic numerical control of the plant enables the control in *normal* or correct operation of the process but presents several problems when the process is under *abnormal* operation and heuristic or experiential knowledge are required (bulking, rising…), or when there are unforeseen situations such as mechanical fault or when the available information is incomplete. Classically, the plant manager or process operators supervise and finally, decide to deactivate or not this automatic control device (manual control) but our approach is to integrate it with the whole reasoning task of the Supervisory System.

7.4 Rule-Based System Implementation.

All the knowledge acquired from literature, interviews and automatic acquisition methods was gathered, structured and combined to adapt the decision trees to the real problem-solving strategies of the expert. Every path or branch of the final decision trees was codified as a production rule (see Figure 30), often heuristic, to conform the knowledge base of the expert system developed into the G2 shell.

```
SVI-TREND = the current value of the SVI of as-reactor - the average value of the SVI of as-reactor between 48 hours
ago and 24 hours ago;

IF the SVI of as-reactor has a current value and the SVI of as-reactor > the lower-limit-SVI of granollers-ranks-es THEN
conclude that the SVI of granollers-qualitative is QUITE-HIGH
ELSE IF the SVI of as-reactor has a current value and the SVI of as-reactor > the higher-limit-SVI of granollers-ranks-es
THEN conclude that the SVI of granollers-qualitative is HIGH
ELSE IF the SVI of as-reactor has a current value THEN conclude that the ivl of granollers-qualitative is NORMAL;

IF the SVI-TREND has a current value and SVI-TREND > the lower-limit-SVI of granollers-ranks-es THEN conclude that
the SVI-TREND of granollers-qualitative is INCREASING
ELSE IF SVI-TREND has a current value and SVI-TREND < 0 THEN conclude that the SVI-TREND of granollers-
qualitative is DECREASING
ELSE IF SVI-TREND has a current value THEN conclude that the SVI-TREND of granollers-qualitative is KEEPING ;
```

```
IF (( the SVI of granollers-qualitative is HIGH or the SVI-TREND of granollers-qualitative is INCREASING) AND
(the FILAMENT-PREDOMINANT of actual-as-floc is not none and the ABUNDANCE of the filament-bacteria named by the
filaments-predominant of actual-as-floc >= 4)
THEN START BULKING-CHECKING MODULE
```

Figure 30 Piece of coded KB showing the type of rules extracted from decision trees.

The whole collection of extracted rules conforms the Knowledge Base (KB) of the Expert System. The structure of this KB is modular, using meta-rules to determine which other module/rules are to be used to solve the problem. Each module has a specific task and consists of different sets of rules, methods and/or procedures. Figure 31 shows the modular structure of the KB with the following modules: Data abstraction, meta-diagnosis, diagnosis and integration.

Once the ES is launched, it gathers required data from the database. Then, the Data **abstraction** module carries out a qualitative abstraction of the whole data (*e.g.* IF TSS-Effluent > 35 g/m^3 THEN TSS-Effluent is high). Based on this qualitative abstraction, the **Meta-diagnosis** module determines which tree and diagnosis paths (*i.e.* decision rules or procedures) are explored to infer the situation.

The whole heuristic knowledge to identify or prevent the WWTP problems conforms the **Diagnosis** module and is grouped into three sub-modules: a) the Fault Detection module, b) the Operational Problems module, and c) the Transition states module. When a problem situation is identified, the inference engine of the ES launches the rules that must determine the causes of this process state. If the right cause is determined, a specific action is recommended. In case the cause is not successfully determined, a non-specific action is proposed to reduce the effects of the trouble. Finally, if different problems have been diagnosed, then the **Integration** module accomplishes the integration of the different information and solutions provided by the ES. Each module will be widely discussed in the following sections.

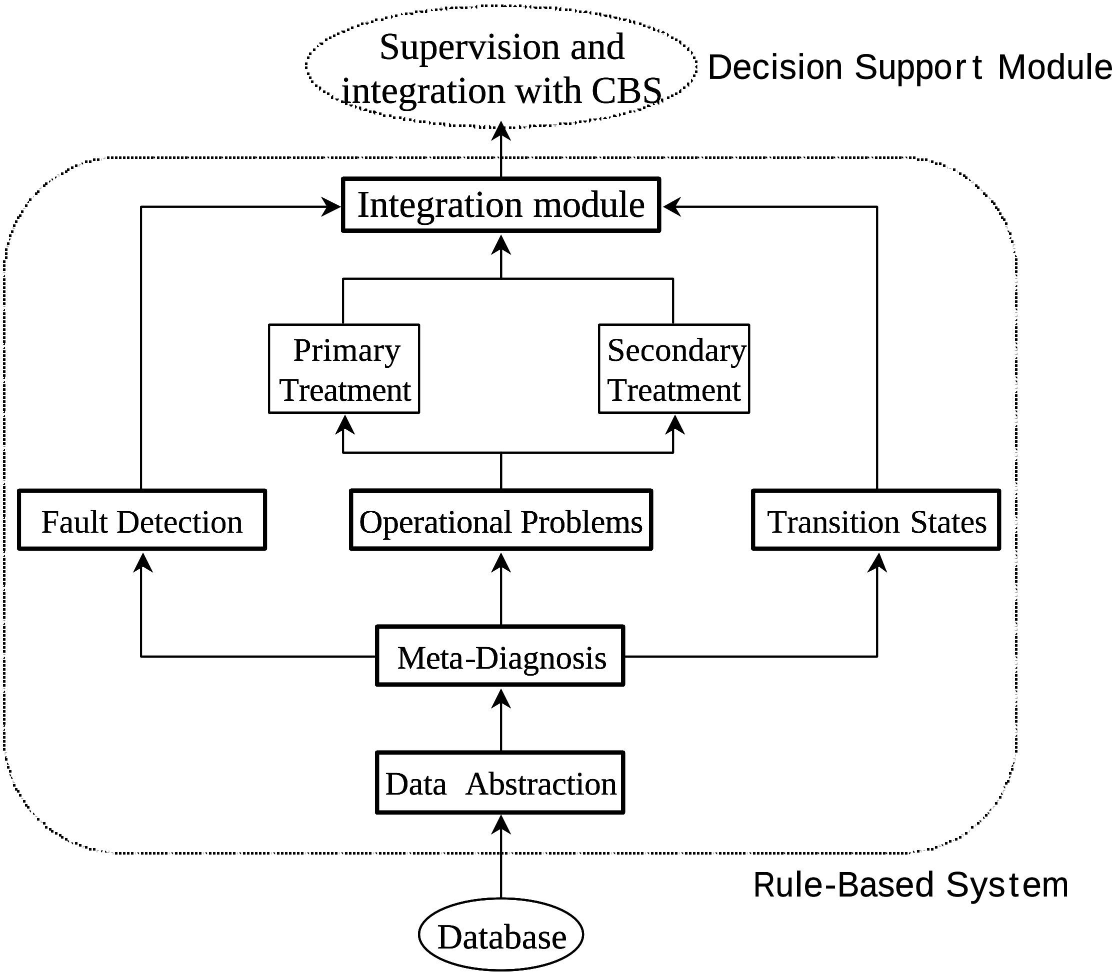

Figure 31 Modular structure of the Expert System

7.4.1 Data abstraction module

The data abstraction module includes a set of rules to conduct a qualitative abstraction of the whole data set (the implementation has resulted in five procedures and 480 lines of code). The computer system performs two types of abstraction:

- conversion of current data to qualitative modalities. For example, *If Effluent-TSS > 35 g/m^3 Then Effluent-TSS is high*
- conversion of current trends of variables to qualitative modalities. For example, *if SVI-trend (slope of SVI trend chart) > 15 then SVI-trend is increasing*

The qualitative modalities low/normal/high and increasing/maintaining/decreasing must be defined for each variable to enable this qualitative abstraction. These modalities were established first by means of a statistical study and then, they were supervised by the expert. For each variable, we represent the data available in a histogram. Normal conditions were defined as the range of values that accounted for the 70% of all data, low and high conditions were defined as those values < 70% and > 70%, respectively. Sometimes there are values very far from the thresholds of the low-normal-high modalities, in those cases, extreme modalities were defined (very-low or excessive). As an example, the graphs of Figure 32 show the histograms for the influent COD. The graph on the left represents the original histogram and the one on the right shows the bars accumulating the 70 % of cases. Table 16 shows the modalities for influent-COD obtained after the statistical study and the expert supervision. Once this was done, the results were checked by the expert to fit the ranges. Simultaneously, the experts defined and adjusted the modalities for all trend variables. At any moment during the BIOMASS operation, the ranges for the ES can be changed interactively through the BIOMASS interface.

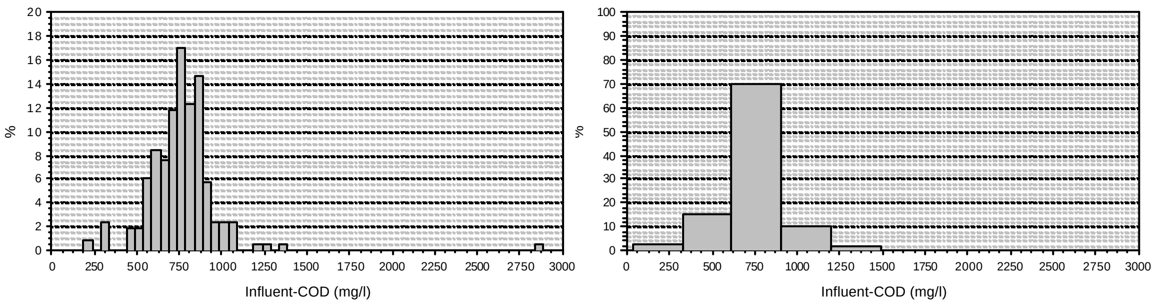

Figure 32 Histograms of the influent COD (left: original and right: 70% accumulated).

Modalities for influent COD (mg/l)	**Low**	**Normal**	**High**	**Excessive**
	< 70 %	70 %	> 70 %	
from histogram	(0 - 600)	(600 - 875)	(875 – 1750)	(> 1750)
adjusted by expert	(0 - 700)	(700 - 950)	(950 – 1750)	(> 1750)

Table 16 Modalities for the abstraction of influent COD to qualitative values.

This qualitative approach enables an easy adaptability of most of the rules of the ES to others WWTP by only changing the numerical values of the modalities.

7.4.2 Meta-Diagnosis module

The diagnosis of WWTP problems, as in any other complex problem, consists of comparing the actual behaviour of the process, as manifested by the values of the operating variables, with the predefined abnormal or threshold values (low, normal, high, very-high). This meta-diagnosis process evaluates the impact of problems, selects those that have crossed a predefined threshold and launches the corresponding diagnosis rules to identify the offending problem and causes that resulted in the observed behaviour. This whole process is done by inference through the representation of knowledge.

Therefore, based on the qualitative abstraction, the rules contained in the Meta-Diagnosis module determine which tree and diagnosis paths (*i.e.* decision rules or procedures) will be explored to infer the situation. This knowledge that decide which rules should be considered and which ones should be rejected is referred as meta-knowledge or meta-rules, according to AI nomenclature. As pointed out by [Jackson, 1999], meta-rules are distinguished from ordinary production rules in that their role is to *direct* the reasoning required to solve the problem, rather than to actually *perform* that reasoning. In the knowledge representation of the ES (decision trees), the meta-knowledge is symbolised by the intermediate alarms. If the intermediate alarm is fired (any of the signs of the problems are fulfilled), then some other branches of the diagnosis tree will be explored. An example of meta-knowledge is the following rule to direct inference reasoning to the exploration of the filamentous-bulking decision tree:

if (the svi of ps-qualitative = the symbol HIGH or the svi of ps-qualitative = the symbol QUITE-HIGH or the svi-trend of ps-trend = the symbol INCREASING or the current value of the filamentous-presence of actual-AS-floc = the symbol high) then INVOKE BULKING-RULES

In the Granollers application, meta-knowledge has been implemented in 11 meta-rules and 104 lines of code.

7.4.3 Diagnosis module

The whole expert knowledge necessary to deal with the detection, management and prediction of any WWTP trouble and causes is grouped into three main sub-modules (see Figure 31): Fault detection, Operational problems and transition states module. Each module comprises several problems, each one with their set of diagnosing, cause detection and action and/or alarm rules. These rules have been extracted from the logic decision and action trees, which were built following the reasoning of the expert. Whenever the diagnosis rules of a problematic situation are launched by meta-diagnosis (a situation is *possible*), then the diagnosis rules attempt to confirm this situation, and the cause detection rules try to find the troubles that cause the abnormal situation.

i) *Fault Detection module,* which includes all the knowledge related to the detection and advisement of operational faults due to plant mechanical equipment or electrical failures of the primary or secondary treatment process equipment (8 rules and 203 lines of code). Some of the elements of WWTP can suffer mechanical or electrical alterations due to the aggressive environment of the plant (*e.g.*, damaged or clogged pumps or pipes, electrical fault detection, air system failure, sludge removal system break, abnormal levels of the tanks, etc.).

ii) *Operational Problems module,* which includes the knowledge for diagnosis and troubleshooting of any primary or secondary treatment problem (55 rules and 156 lines of code for a total of 21 operational problems). These problems were also divided into biological and non-biological nature depending on the cause of the dysfunction, (*e.g.*, old sludge, foam, filamentous bulking, slime viscous bulking, deflocculation, storm, foaming, hydraulic shock, under loading, solids overloading, organic overloading, toxic shock, low pre-treatment efficiency, etc.)

iii) *Transition states module*, which contains all the knowledge necessary to cope with transient states that can evolve towards undesirable problems contained in the previous module. The goal is to detect situations that may lead to a fault state, although they are not classified as fault yet (to detect situations that could lead to a problem). Although the causes of a problem may be already present, sometimes the process takes a long time (days or weeks) to reveal some symptoms of malfunctioning. Therefore, this module is composed of a set of 77 rules to scan the process looking for any cause that could lead to a problematic situation, identify it and act in order to correct the problem before it appears. This module attempts to imitate human experts in their ability to predict possible future problems when a specific symptom occurs. These sets of rules try to detect the transitions towards a problematic situation by monitoring the temporal evolution of some variables. For example, trends towards low pH at the influent, low or high F/M ratios, low or high dissolved oxygen can be indicators of a transition to a filamentous bulking situation, since these parameters are causes that can lead to Bulking within few days.

Some of the tasks of fault detection module could also be accomplished by a standard SCADA, which can advice the expert by sending an alarm sign and suggesting some quick actions, while the second and third diagnosis modules can only be tackled with the use of knowledge-based systems.

Whenever a problematic situation or a transition state to some problem is identified, the diagnosis task of the ES is complemented with the detection of the cause of the problem. Therefore, the inference engine activates the rules that must determine the possible causes of the problem detected. As an example, the following rules correspond to the cause detection rules for filamentous bulking:

if the DO of O2-parameters is low then conclude that the DO of bulking-causes is true
if the F-to-M_ratio of ps-qualitative is low then conclude that the f-to-m of bulking-causes is true
if the influent-ph of ps-qualitative is low then conclude that the ph of bulking-causes is true
if the BOD-to-N_ratio of ps-qualitative is inadequate or the BOD-to-P_ratio of ps-qualitative is inadequate then conclude that the N-nutrient-deficiency of bulking-causes is true
if the septicity of ps-qualitative is high then conclude that the septicity of bulking-causes is true

In our particular study there were a total of 62 rules for cause detection of operational problems and 26 rules for cause detection of transition to a problem. If the right cause of the problem is determined, a specific action is recommended. In case the cause is not successfully determined, a non-specific action must be proposed to soften the effects of the trouble without tackling the real cause. The Expert actions were codified into 30 rules and more than 2500 lines of code within 85 procedures.

7.4.4 Integration module

Finally, if different problems have been diagnosed, then the Integration module accomplishes the integration of the different information and solutions provided by the Expert System. This module was made up of 149 lines of code whose objective was to compile and process the whole information received from the ES (*i.e.*, which problems have been detected, which are the causes and which are the suitable action proposed) evaluating any possible conflict and avoiding contradictory results.

7.5 CBS Implementation

A prototype of case-based reasoning shell for developing case-based systems (Opencase) was already implemented in Common Lisp[1]. The Case-based system developed over Opencase was implemented by searching and retrieving algorithms, which are detailed in chapter 6, by a case-library with hierarchical memory and a prioritised order of the attributes. However, at the early phase of the implementation of BIOMASS, a simplified CBS with plain memory was also implemented into the G2 shell and performed successfully with small case libraries (less than 300 cases). The implementation of this CBS with plain memory into G2 has resulted in about 500 lines of G2 code and a function to codify *L'Eixample* distance. In fact, at the beginning of the field validation when few cases were available, a flat memory should be used but as the case-library increases in information (*i.e.*, number of cases), it is recommended to begin using a hierarchical memory to speed the case retrieval phase.

The next two sub-sections briefly detail the concept of the two models used in the decision support module of the Supervisory System.

7.6 Mechanistic Model

A mechanistic model of the treatment process of the plant was developed using the GPS-X commercial software [Hydromantis, 1995]. The biological reactor was modelled as four Continuous Stirred Tank Reactors, while primary and secondary settlers were modelled with a model that considers one-dimensional tank with 10 layer of solids flux without biological reaction. An exhaustive calibration procedure is still being carried out to adjust the kinetic, stoichiometric and settling parameters of the ASM2 model [Henze *et al.*, 1995] of this plant. The standard values for these parameters given by the GPS-X were used in the first simulations except for those that were more relevant which were changed manually. Figure 33 shows the flow sheet of the Granollers WWTP implemented in GPS-X. A mechanistic model enables to simulate several *off-line* scenarios with different operational conditions, changes in the influent characteristics (underloading, overloading, storms…), and alternative actions proposed by the Supervisory System. In spite of these capabilities, these kind of models present limitations when dealing with problematic situations of biological origin (filamentous bulking, foaming, rising…) as well as with situations for which it has not been calibrated. In this sense, the utilisation of soft-computing techniques to build a non-mechanistic model to simulate the behaviour of the plant at any situation is also being studied.

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[1] Common Lisp is a functional programming language that provides a programming environment to writing large, complex programs that can manipulate symbols as well numbers

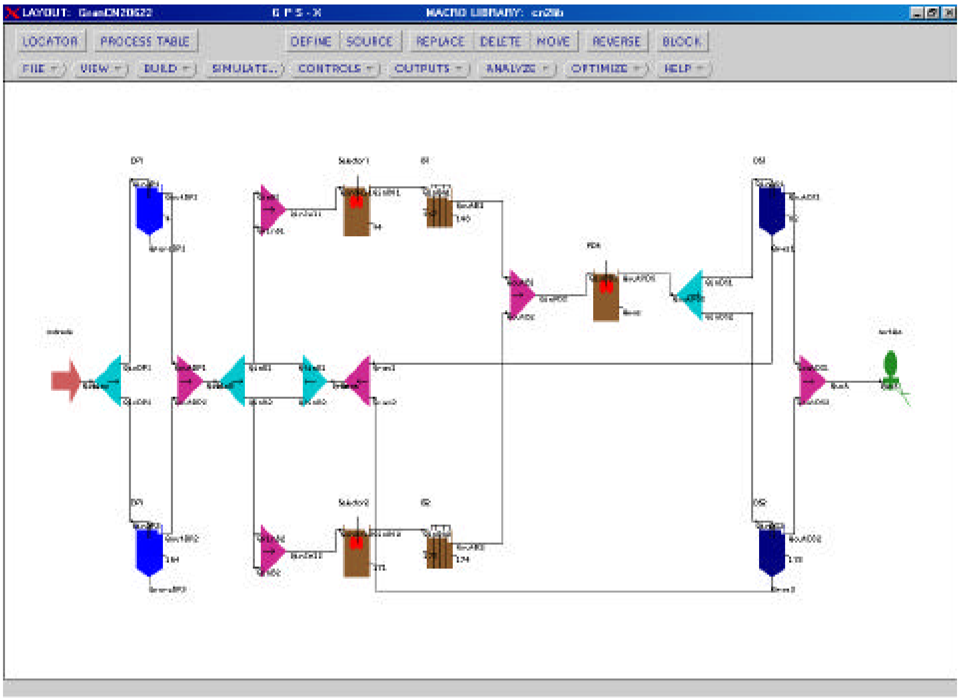

Figure 33 Flow sheet of the Granollers WWTP implemented in GPS-X.

7.7 Non-mechanistic or *Black-box* model

To be able to characterise the behaviour of the plant under any situation, but mainly under abnormal situations that cannot be modelled by a mechanistical model, another research line has been initiated to identify a model that may predict the plant performance with reasonable accuracy. This is accomplished by using methods that fall within what is nowadays labelled as soft computing methods, among which we find rough sets theory, fuzzy sets theory, and artificial neural network learning.

Fuzzy Logic brings a formalism with its own syntax and semantics capable of expressing qualitative knowledge about the problem under study. Its excellence relies specially in the strength of its interpolative reasoning mechanism. *Rough sets* exploit the idea of approximating a set by other sets. In particular, the goal is to find a minimal subset of interacting variables having the same discriminatory power as the original ones, which would lead to the elimination of irrelevant or noisy variables, without the loss of essential information. *Probabilistic neural networks* is a reformulation of the Bayes - Parzen classifier - a classical pattern recognition technique - in the form of a neural network. Besides the input layer, there is a so-called pattern layer with as many neurons as patterns are included in the training set. Next, a summation layer contains one neuron for each class that leads to the output layer. Each pattern-layer neuron computes a distance measure between the input and the training sample associated with the neuron. The activation functions of these neurons are Parzen windows used to collectively approximate the probability density functions required by the classifier. In essence, it provides ways of updating the expected results in light of new acquired knowledge. Also the *k-nearest neighbour* (*k*-NN) algorithm (with $k = 3$) was tested against the data in some experiments as a further reference (this algorithm has no training phase). In the nearest neighbour (NN) pattern classifier algorithm, when classifying a new example, the Euclidean distance between that example and all training examples is calculated and the class of the closest training example is assigned to the new example [Dasarathy, 1990]. The more general *k*-NN method takes the *k* nearest training examples and determines the class of the new example by majority vote. In improved versions of *k*-NN, the votes of each of the *k* nearest neighbours are weighted by the respective proximity to the new example. A more detailed description of NN algorithm, and of how distance computation, classification, and feature weighting is performed, is given in the appendix. Instance-based learning (IBL) algorithms are derived from the NN pattern classifier. IBL algorithms use specific instances to perform classification tasks, rather than using generalisations such as induced if-then rules [Aha *et al.*, 1991]. IBL algorithms are also called lazy learning algorithms, as they simply save some or all of the training examples and postpone all effort towards inductive generalisation until classification time. They assume that similar instances have similar classifications: novel instances are classified according to the classifications of their most similar neighbours.

In particular, time-delay neural networks of three kinds are used: classical (trained with simulated annealing plus conjugate gradient) [Hertz *et al.*, 1991], probabilistic (trained as a Bayes-Parzen classifier) [Specht, 1990], and heterogeneous (trained with genetic algorithms) [Valdés and García, 1997].

A time-delay neural networks (TDNN) is a multi-layer feed-forward neural network that enables to turn a temporal sequence into a set of spatial patterns on the input layer. In these networks, several values of a fixed-length segment with the most recent input data from an external signal are presented simultaneously at the network input using a moving window. Their main advantage in front of recurrent networks is their lower cost of training, which is very important in the case of long training sequences.

The *classical neural network* used is the so-called Multi-Layer Perceptron where the neuron model is the usual scalar-product followed by the logistic function. This network is trained by means of a hybrid procedure composed of repeated cycles of simulated annealing coupled with the conjugate gradient algorithm (which we will call Time-Delay Multi-Layer Perceptron –TDMLP-).

Heterogeneous neural networks are neural architectures built out of neuron models which allow heterogeneous and imprecise inputs (reals, fuzzy sets, ordinals, nominals and missing data. This network was trained using a standard genetic algorithm with parameters to avoid over-fitting.

7.8 First layer: data analysis and interpretation module

The first layer of the Supervisory System comprises data collection or acquisition, processing and monitoring of the whole data generated by the WWTP in order to have an updated plant state information; and off-line knowledge acquisition process of new knowledge from plant feedback. The data processing includes the validation, integration and registration processes.

7.8.1 Data acquisition or data collecting

A data acquisition system for the Supervisory System was successfully developed to continuously gather all kind of data collected in the facility and store it into the evolutive database. Three types of data were distinguished: on-line data coming from sensors and equipment, off-line data (both numerical and qualitative) and inferred data.

7.8.1.1 On-line data

On-line data include about 200 digital signals about the state of the mechanical equipment of the plant (pump engine switched on/off, blower functioning at high/low velocity, electrovalve open/closed, floodgate open/closed, the status of automatic grids engine (on/off)…). Excluding these mec hanical signals, on-line data also includes 20 analogical signals generated by the sensors: flow rates (influent, primary effluent, effluent, by-pass, recycle, wasting, recirculation and aeration) and physical parameters like pH or dissolved oxygen concentration at each compartment of the aeration tank. On-line data acquisition is directly accomplished from the PLCs network of the plant. These PLCs are connected to a Master-PLC, which transmits every 15 seconds the whole on-line data via RS-232 to the PC where a Data-Server program and BIOMASS resides. This Data-Server program is in charge of communicate with the Master-PLC via RS-232 using a set of predefined messages (33 rules and 73 lines of code within 4 procedures). The Data-Server was built with G2-Gateway [Gensym, 1997b], a tool to develop extern data acquisition systems for G2, with capabilities to handle communication requirements, synchronising tasks, protocols…to obtain values from external sources and set values in external applications. It is also able to receive a data request from G2 at any moment, and to answer immediately. This communication is established via TCP/IP.

7.8.1.2 Off-line data

Off-line numerical data provided by the analytical determinations of samples collected daily from different locations in the plant and off-line qualitative data provided by daily *in situ* macroscopic observations. The in-situ observations comprise plant performance, quality of biomass, and settling characteristics and can be directly read from the laboratory database once a day. Firstly, the analysts utilised Excel as database recorder but they soon changed to LIMS, database management software developed in Oracle, resulting in a database management system that provides a more powerful access to and manipulation of a relation's database. In both cases, G2 can directly read the data using the bridges G2-ActiveXLink (for excel, [Gensym, 1997b]) or G2-ODBC (for Oracle, [Gensym, 1997b]). Alternatively, as we did not have these two applications, a data acquisition system, that performs data import and export functions, was developed to read an ASCII file generated from either Excel or Oracle (1510 lines of code within five procedures). The next piece of code is used to read ASCII files:

```
open-file-for-read (filename: text, WS: class kb-workspace, arrayname: class text-array , nline: integer, m: class text-display-message )
text-file-stream: class g2-stream;
line: text="";
j: integer = 0;
begin
text-file-stream = call g2-open-file-for-read(filename);
```

```
call g2-set-file-position (text-file-stream, 0, false);
conclude that the array-length of arrayname = j + 1;
    repeat
        line = call g2-read-line(text-file-stream);
        line ="[line],";
         conclude that arrayname[j] = line ;
        j = j +1 ;
       exit if j = nline + 1;
       conclude that the array-length of arrayname = the array-length of arrayname + 1;
    end;
conclude that the array-is-permanent of arrayname  = true ;
call g2-close-file (text-file-stream);
end
```

And for exporting data to an output file:

```
procedure-for-registering-messages (filename: text, message: text )
text-file-stream: class g2-stream;
line: text= "";
counter: integer = 0;
j:integer=0;
long: integer;
begin
text-file-stream = call g2-open-file-for-read-and-write (filename);
call g2-set-file-position (text-file-stream, file-position, true);
collect data ( timing out after 1 second)
line = "[the current day of the week] [the current day of the month] [the current month] [the current year] [the current hour] [the current minute] [the current second]: [message] ";
end;
call g2-write-line (text-file-stream, line);
long= call g2-length-of-file (text-file-stream);
conclude that file-position = long;
call g2-close-file (text-file-stream) ;
call g2-close-all-files ();
call send-message-to-message-board (message-board, nRow , 3, message )
end
```

As stated before, an expert who is not the plant manager nor the operators takes the microbiological determinations in the Granollers WWTP once a week. These determinations are not registered periodically in the same fixed day (it depends on the scheduled work of the expert), therefore, it is quite difficult for the system to read these microbiological data regularly, so its introduction to G2 with end-user controls through the PC interface was considered to be a good option to import these data into the Supervisory System. Figure 34 shows the dialog interface with type-in boxes (or buttons) to introduce the microbiological information of the activated sludge to the computer system.

Alternatively , we could introduce these data through a WWW page using an Internet navigator with an ActiveX container or generating an e-mail (ASCII file) from the WWW page to the PC containing the Supervisory System [Baeza, 1999].

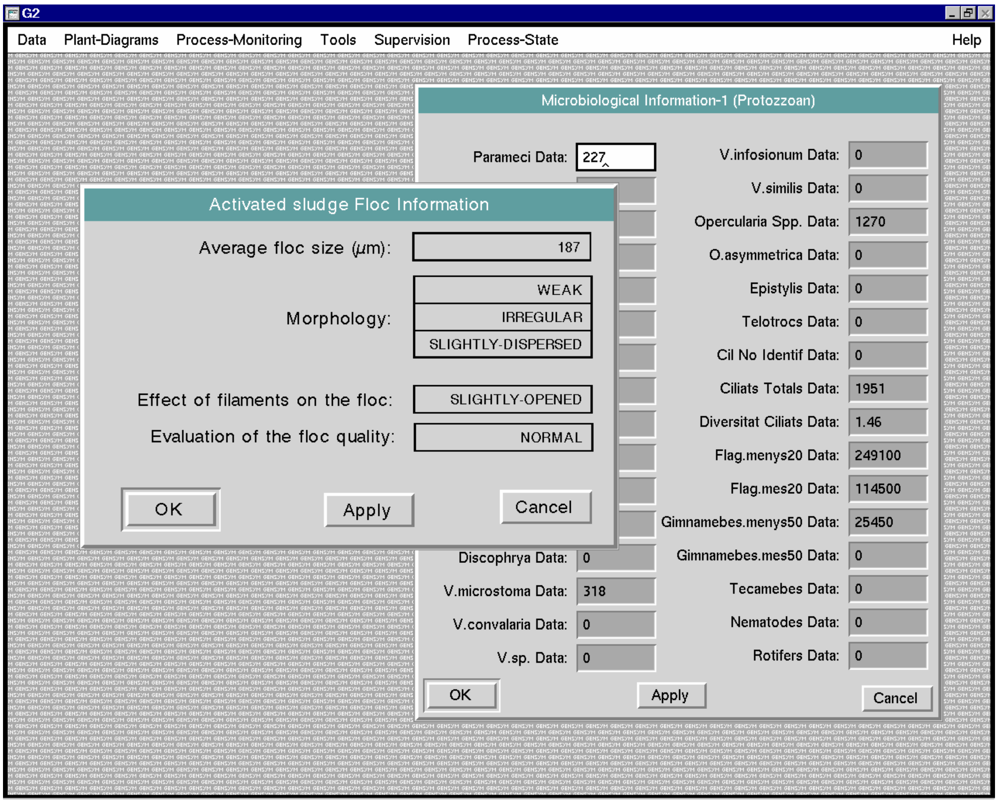

Figure 34 User-menus for the introduction of microbiological data through the PC-interface.

A module to support the filamentous organisms and microfauna identification to low level skill operators was developed over G2 based on [Jenkins *et al.*, 1993], [Madoni, 1994] and other literature sources. It supports the identification by asking for some evident organisms features observed with a microscope. For example, the presence or absence of branches in the filaments, the cell-shape of filaments, the presence of flagella, cilia or pseudopodia in protozoan, the formation or not of colonies…(105 rules and 401 lines of code within 63 procedures carry out this task). Moreover, when the microorganism is identified, the microbiological-support-module gives information to the user about the significance of its presence.

7.8.1.3 Calculated and inferred data.

Combinations of numerical data allow calculating global process variables such as Sludge Residence Time, Sludge Volume Index, F/M ratio and the percentages of COD, BOD and SS removal of primary, secondary and overall treatment. Besides, once the microbiological data is introduced into the 59 G2-objects containing microscopic information (including different filamentous and microfauna species and activated sludge characterisation), a set of 7 rules and 344 lines of code calculate the relative abundances of the different microbiological species (*none*, *few*, *some*, *common*, *abundant* or *excessive* modality is assigned to each specie) and the predominant filamentous organism and protozoan.

7.8.2 Data processing (validation, integration and registration)

Original raw data require a number of processing procedures to validate and to integrate the data into one uniform time-scale before being stored into the database. These procedures can be divided into data validation and data registration for the whole data, and data integration to keep the history of the on-line data.

Data **validation** must include checking for correctness of the data values, timely, periodicity and existence of the data or not. The validation procedures implemented to deal with these problems and to ensure valid data include. This step comprises 8 rules and 126 lines of code within 8 procedures. The tasks conducted can be resumed as follows:

- a monitoring procedure to check the values of the data (if not correct, *i.e.*, negative or out-of-range values for chemical analysis of wastewater and sludge quality, *e.g.* inflow flow rate cannot be lower than 5000 m^3/d neither higher than 35000 m^3/d).
- procedures to properly update the data (in case of non-timely data). All the variables have a validity time interval for their values. Once this interval has been overcome, the stored value of a variable is useless, and a new value has to be acquired by means of the Data Acquisition system and has to be sent to the Data Base. For example, on-line data are updated every 15 seconds while off-line are imported once a day and have different validity intervals (for example, influent COD has a validity of 36 hours while the variable filamentous dominant is valid for 3 days).
- a procedure to rescale or recombine the improperly indexed data (periodicity), *i.e.*, the whole data are homogenised in the same basis (24h). In this sense, daily-accumulated values for the water and sludge flow rates are calculated to know the amount of wastewater treated, the wastewater by-passed, the primary sludge wasted and the secondary sludge recycled, recirculated and wasted every day. For the rule-based system operation, the average value during the last 3 days for certain variables with high variability and low frequency of collection (*e.g.*, influent TKN) is preferred over the last collected value.
- a procedure to detect whether the data exist or not in a machine-readable form and whether it was measured or not.

The data **integration** procedures enable to filter and reformat data coming from sensors (water and sludge flow rates, DO, Air flow and pH) to obtain 5-minutes, 1-hour, and 24-hours averaged values. The derivatives of some specific variables are also calculated to detect sudden changes.

The data **registration** procedures record the whole data in a daily record of the plant into the evolutive database from where every reasoning module (ES or CBS) will obtain the data. The daily record include the accumulated values of data coming from sensors together with the analytical values, observations, microbiological information and inferred data. Additionally, the 5-minutes and 1-hour averaged values are also recorded in ASCII files for possible later use.

The continuous update of the database and supplying of the most recent data is key for a successful and useful performance of the Supervisory System. Throughout the inference process of the Supervisory System, it could find some value that has not been updated yet. In that case, the system would search the most recent value collected and would use it in case it has not expired. Otherwise, if the inference engine cannot follow any other diagnosis path, it should be directly requested to the user.

Because WWTPs are dynamic systems (that change their behaviour over the time), the optimal monitoring of the process state must include not only the information about the current state of the plant but also the previous historical data about the quality of water and sludge at different sample points and operational parameters (aeration, recycle, recirculation, and wasting rate). Thanks to the capabilities of G2, the previous temporal values stored in the database and the current information enable BIOMASS to carry out a temporal reasoning to identify trends of relevant variables that could indicate transitions to an operational problem, according to the expert system reasoning.

7.8.3 Data monitoring

The on-line process monitoring consists in displaying all different data to allow the plant manager to make an easier interpretation of the large quantities of data generated within the plant. Any kind of graphic (trend-charts, (x,y) plots, statistical graphs…) can be defined and accessed from the top bar menu. Graphics that were mostly consulted include instantaneous, hourly and weekly water flow rates, dissolved oxygen level, air flow rates, influent COD and TKN, F:M ratio and upflow velocity (see Figure 35). The on-line process monitoring enables the system to make any of the functions carried out by a typical SCADA.

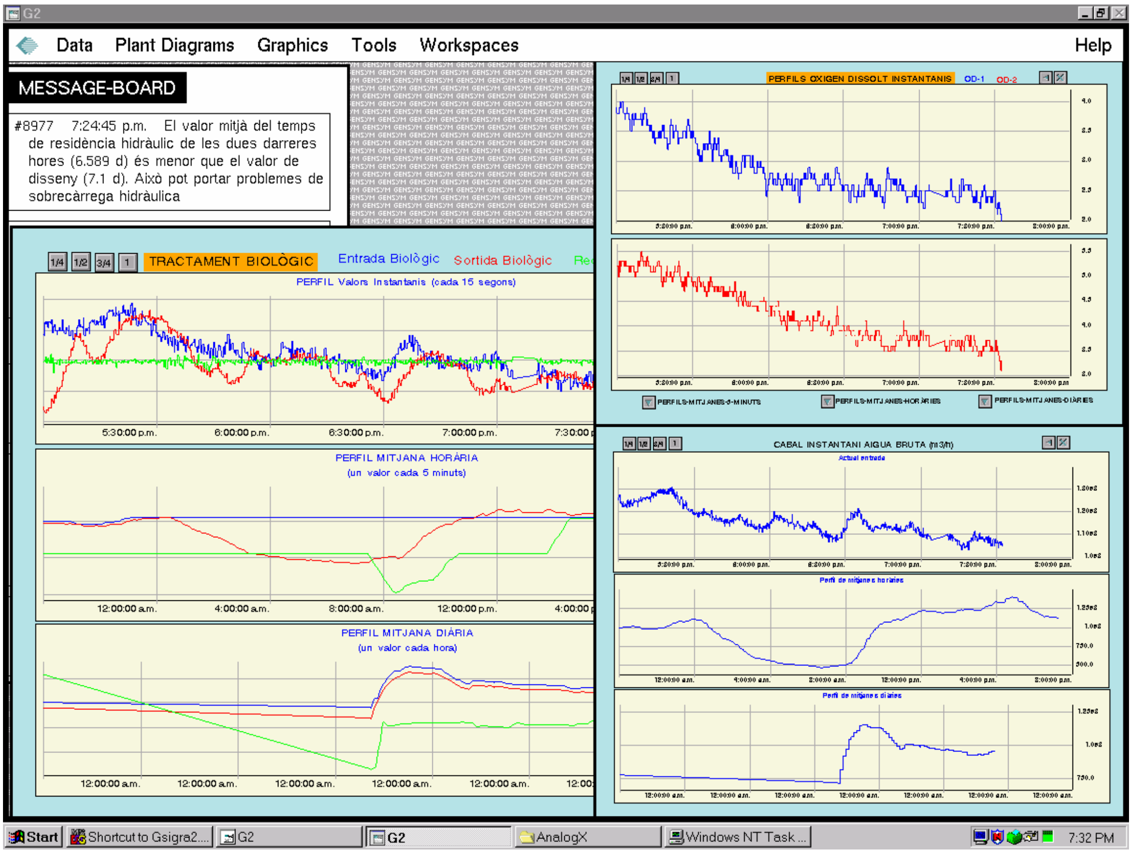

Figure 35 Visual monitoring on the Supervisory System.

7.8.4 Knowledge acquisition

The knowledge acquisition sub-system uses different *off-line* knowledge acquisition techniques for automatic generation of inference rules as the result of a previous classification process of attributes and observations, defined by experts (Linneo$^+$) or as the result of an inductive learning process (CN2 and C4.5).

7.9 Second layer: diagnosis module

The second level of BIOMASS implements the reasoning and integration tasks based on the heuristic knowledge of the ES, the experiential of a CBS which reuses the experience from previous particular situations, in co-operation with the numerical unit based on modelling and computing (classical control methods), to diagnose and handle any operational problem. Figure 36 shows a schematic of the tasks carried out and the tools involved in the diagnosis module of BIOMASS.

Once the information has been gathered and processed, the two systems developed that are based on knowledge (ES and CBS) are executed concurrently to infer the possible state of the plant. They two of them use the same input information, but they do not interact. The system diagnoses the current operational state and trend of the WWTP process, decide whether the system is in abnormal state or not and proposes the suitable action plan according to the information concluded by both the ES and by the CBS. All this information concluded by the rule-based system is sent to the third layer of BIOMASS, where it will be considered together with the result of the case-based system.

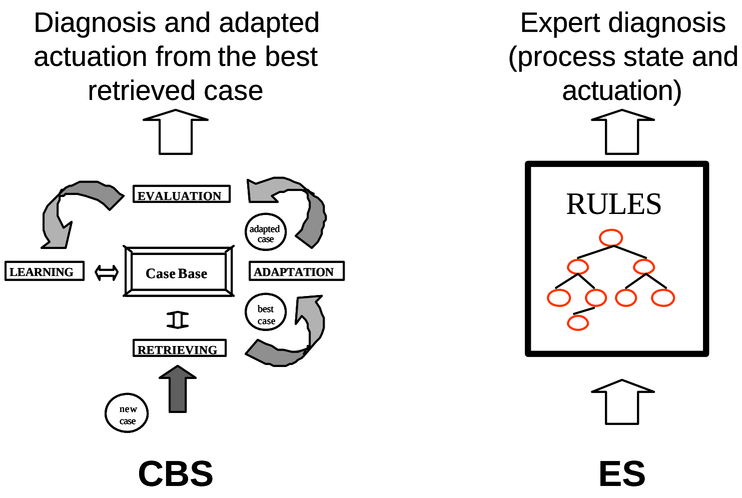

Figure 36 Schematic of the tasks carried in the second layer of the Supervisory System.

7.10 Third layer: decision support module

The third (and upper) layer or level of BIOMASS (the decision support module) performs the supervision and prediction tasks over the WWTP. The supervision task consists of gathering and combining the conclusions from both reasoning approaches (process diagnosis and action proposals from ES and solution for the similar cases from CBS), looking for a consensus, and identifying whether there is a problem or not and thus, to infer whether the plant is under normal or abnormal operation.

If the computer Supervisory System recognises any abnormal situation[7], it will take supervision control and will propose the most suitable action strategy (based on the reasoning procedure that a human expert would do or based on experience for abnormal situations in a particular plant) to maintain the process under control, deactivating or modifying the automatic control, if necessary. A set of supervision rules decide whether the action can be based upon the expert (ES) or experiential (CBS) knowledge. Generally, if one of the retrieved cases is very similar to the current case and it has an action stored, this option will be preferred over the expert action (from ES). If all retrieved cases are quite different from the current case, the action rules according to the problem(s) diagnosed by the ES will be launched.

The final diagnosis and action inferred is communicated to the user through the message-board (see Figure 37) of the computer interface. Then, the system waits for the user validation before carrying out any action on the

[7] An *abnormal* situation refers to the incorrect operation of the plant; it means that some of the pollutant concentrations at the effluent do not fulfil the environmental legal limits (treatment goals are not obtained) or that some of the main operational parameters and influent characteristics are not comprised in normal ranges (that plant is not behaving well).

plant. The expert performs an evaluation of the plans suggested, checking its validity and deciding which is the best strategy to re-direct the process to the correct or the abnormal operation. In *some* controversial situations, a decision support system tool (*i.e.*, a mathematical model or a *black-box* model) can be used to support users to evaluate and decide among different potential action plans to overcome the problem. A calibrated mechanistic model of the plant or a blac k-box model based on heterogeneous neural networks, which simulate off-line the effects of the application of the alternative action strategies suggested over the plant, carries out this prediction task.

According to the predictive results, the plant manager performs a final validation and decides which kind of control will be carried out. The plant manager has always three possibilities: (1) to deactivate automatic control and implement the action suggested by the Supervisory System (the expert, based on the reasoning procedure that the plant manager would do, or the experiential, based on historical cases occurred in the plant). In this case, once the Supervisory System stops concluding the abnormal situation, the automatic control will be re-established. (2) to maintain or modify the automatic control over the plant (*e.g.*, the set points of a closed loop for controlling the dissolved oxygen level in the aeration tank in situations of normal operation) and complement it with the expert or experiential strategy proposed to accelerate the back of process to the normal operation, or, (3), just to maintain the automatic control. Maintenance or activation of automatic control are preferred when the system infers a situation of normal and correct operation. This final supervision supports the decision making process, raising the interaction of the user(s) with the Supervisory System by querying for justifications and explanations about decisions.

Currently, on-line actuators that could carry out automatically some actions from Supervisory System conclusions are still not used to modify any on-line working parameter (*i.e*, modification of the set-points of the numerical control module, modification of sludge or water flow rates, change of any valve or pump position…). There is no automatic action over the plant to solve the problem but there is not a technical problem to do it. This project has a deadline (January 2001) for the system to be completed and evaluated. From this date, we will consider the direct implementation of the action plan suggested by the Supervisory System to the plant. Therefore, when the action plans proposed to maintain the WWTP under control involve more actions than only maintenance of automatic control, manual activities are required.

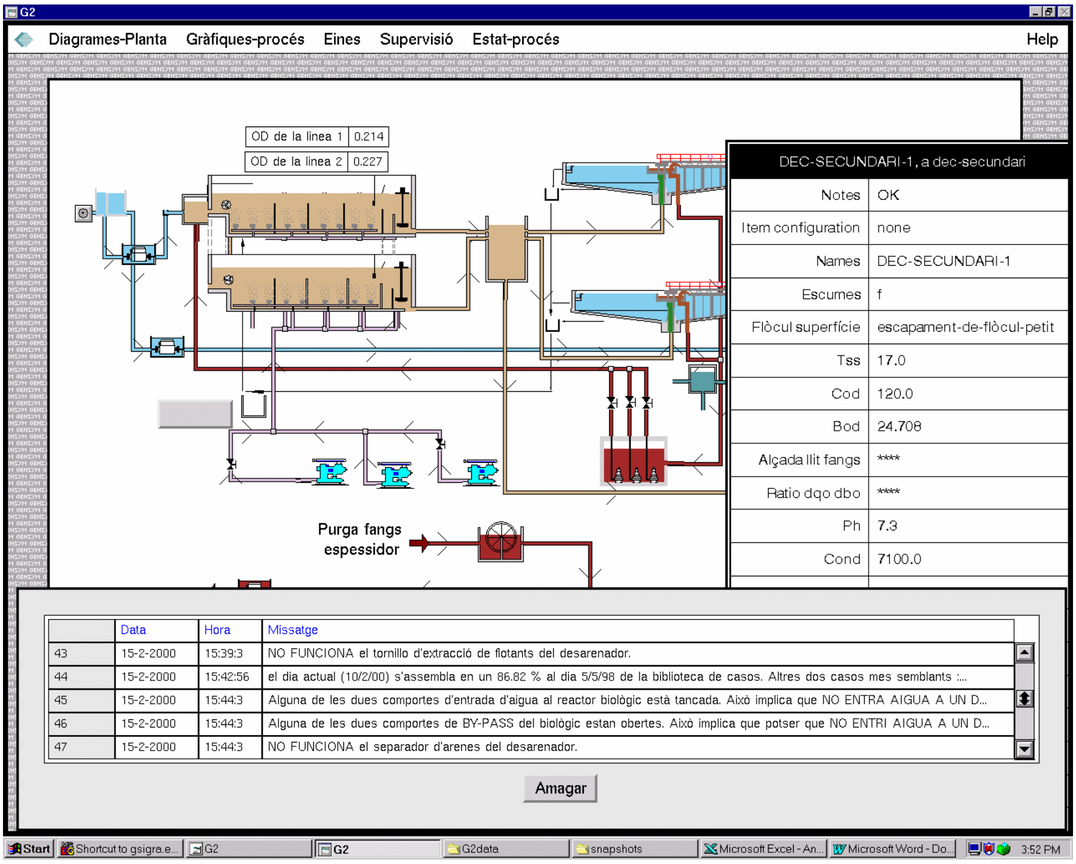

Figure 37 The conclusions of the system are shown through the message-board.

The third layer also provides a user-friendly communication through the user interface. A menu-based interface has been developed over the G2 environment to provide a simple and transparent way for users to run the Supervisory System and to know the state of the process and the evolution of process over time at any time. In this sense, the diagnosed situation (normal, rising, bulking…) can be displayed at any moment until a new supervisory cycle is started. The user can consult not only the agreed conclusion of Supervisory System but also the diagnosis and action plans of ES and CBS separately. This module can also be requested for explanations of the conclusions reached and deductive processes, retrieval of certain quantitative or qualitative values, providing interaction by asking or answering the user and/or system inquiries to the outside world, etc...Moreover, several trend charts, graphics, diagrams of the plant with readouts of the most important values in each unit…make the understanding of large amounts of information generated by the plant easier.

Access control features have been also added to give protection to the system, depending on the type of user considered. Thus, the knowledge base can only be modified by a developer or administrator, but not in user mode. The user can only access the different options of the bar-menu.

The supervisory cycle

The different tasks of the third levels of BIOMASS are performed cyclical, using a supervisory cycle (see Figure 38). Each cycle is composed of six steps: data gathering and update, diagnosis, supervision, prediction, user-validation and action phase and, evaluation phase.

Every time the supervisory cycle is launched, the first task to be carried out is *data gathering* and *updating* the current data for the inference process. Initial procedures carry out these tasks. These are: (i) Update-Data, that is, to gather the most recent data both quantitative and qualitative from the evolutive database. According to the expert, there exists a minimal set of essential variables that must be updated - basic information – for carrying out a reliable diagnosis of the current state of the process. In the Granollers WWTP, these are the influent flow rate and the COD of the biological influent), (ii) Update-Process-State, that is, to conclude that all the variables of the G2-objects containing the information about the process state (Process-Situation, Process-Transition and Cause-Identified) have no current value.

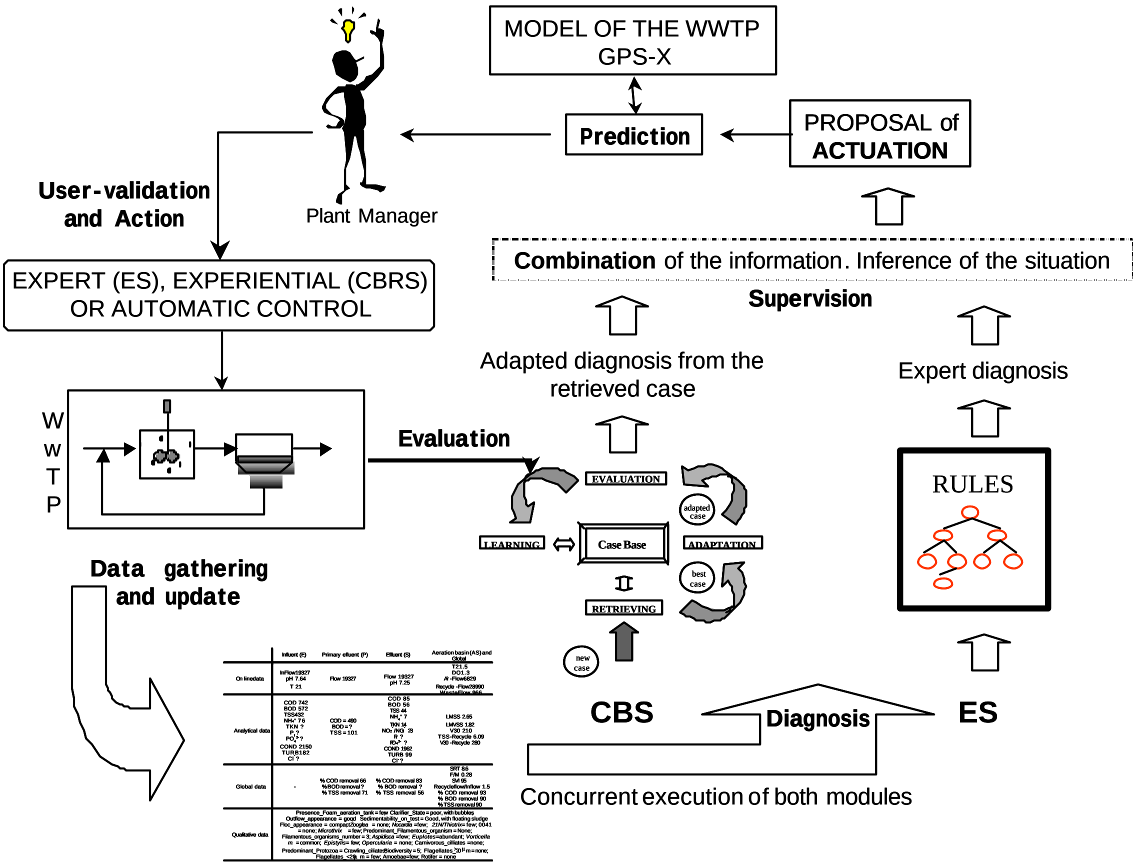

Figure 38 Supervisory cycle.

Once the information has been collected, it is sent to the *diagnosis* module where the knowledge-based systems (ES and CBS) are executed concurrently without any kind of interaction between them. The current state of the process will be diagnosed through a reasoning task carried out by both the expert rules and the most similar cases retrieved. If a problem is detected or suspected, the diagnosis module will also try to identify the specific cause. The solution of the most similar case is modified to adapt it to the new situation. The conclusions of diagnosis phase are sent to the decision support module.

This upper module infers a global situation of the WWTP and suggests a proper action plan as a result of the *supervision* and *prediction* tasks integrating the expert recommendations sent by the ES and the experiential action retrieved by the CBS, while evaluates any possible conflict. The final result of BIOMASS is sent to the operator through the computer interface who will finally decide the action carried out (*user-validation* and *action*). The expert can use the dynamic model implemented in the GPS-X shell or the Neural Network model to support the selection process of an action plan by simulating the possible consequences of applying different alternatives.

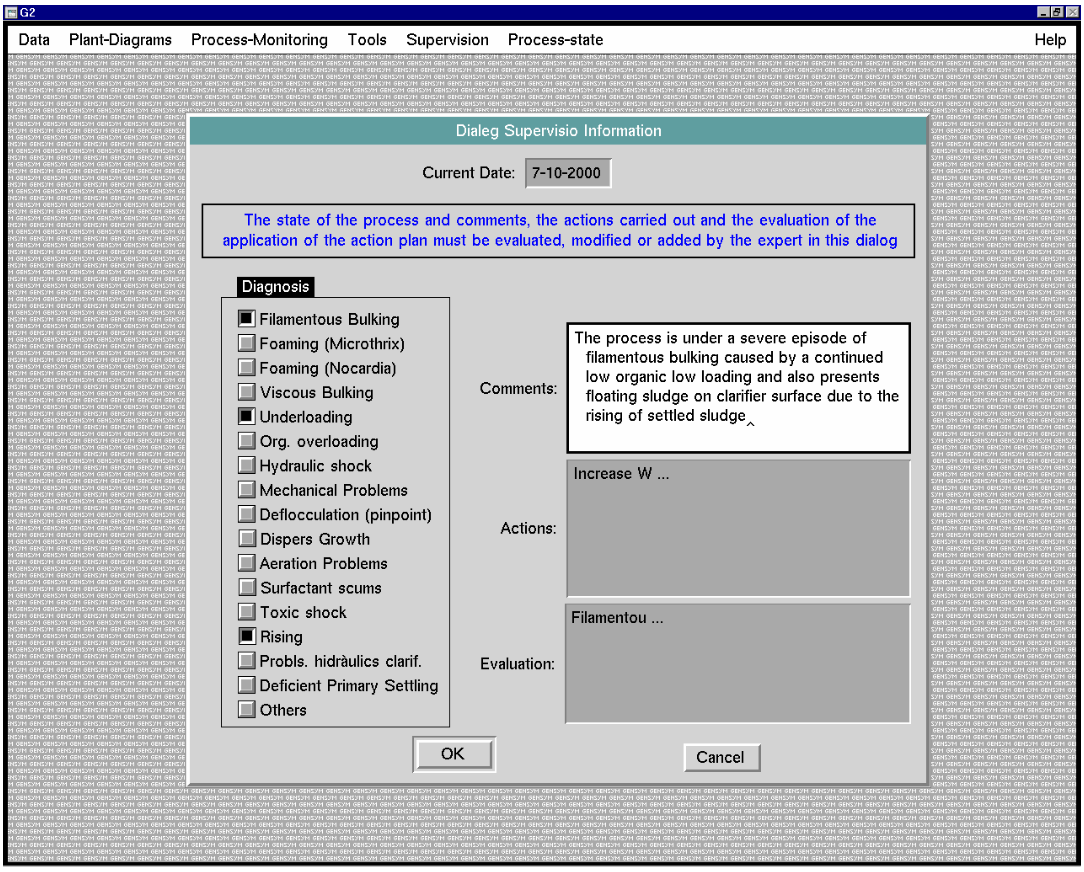

Figure 39 Dialog for registering the evaluation of the actions carried out

Finally, the *evaluation* of the results of the application of the action plan to solve the problem over the process allows the system *closing* the CBS cycle, that is, to learn from failure or successful past experiences and to upgrade the case-library. Thus, if the current case is quite different from all historical cases of case-library, it should be stored as a new experience with the diagnosis and comments of the process state, the action carried out and the evaluation of its application to the plant (see Figure 39). These features can be detected by the Supervisory System itself (unless a manual operation is carried out), but a confirmation from plant manager is indispensable who will be allowed to change misleading or add missing information. On the other hand, the

Supervisory System can also extend the knowledge base by acquiring new knowledge from new sources (new experts or new automatic data classification).

The supervisory task of BIOMASS is started whenever any symptom or alarm of the operational problems is fulfilled (*i.e.*, these alarms or symptoms involve anomalous values of the variables continuously scanned for normal operation) but, at least, the supervisory cycle is routinely executed once a day at pre-defined time intervals using daily averaged data. It can also be started manually whenever the operator requires it. Moreover, the two knowledge-based systems can be activated jointly or each module (ES or CBS) separately. The codification of the general inference to carry out this supervisory cycle involved 11 rules, and 715 lines of code within 25 procedures.

8 EVALUATION OF THE SUPERVISORY SYSTEM

8.1 Introduction

This chapter gives attention to the single evaluation of each technology involved in this hybrid intelligent architecture and to the field validation of the overall system as a real time Supervisory System for WWTP operation and control.

Evaluation is referred to the whole set of tasks involving checking, detecting anomalies, assuring adequacy, etc. conducted during BIOMASS construction. The main objective of the evaluation process is to ensure that BIOMASS provides the correct answer in the correct form. To do this, we should discover and eliminate any source of errors or inadequacies from BIOMASS. They are introduced during the different phases of the system construction (design of the system, knowledge acquisition and implementation). The major causes or errors are as follows:

- Lack of system specifications and poor understanding of the problem. Moreover, semantic as well as syntactic errors introduced during the implementation
- Erroneous solutions or inability to find any solution to the problem (in an expert system, due to incorrect representation of the domain knowledge)
- Unsatisfactory relation with the user
- Unsatisfactory relation with the organisation into which it is integrated

Each one of these four error types is related to the four types of evaluation: verification, validation, ease of use of the system (usability) and its readiness for use (usefulness). However, other researchers consider the term Verification and Validation (V&V) as a suitable name for the mechanism for the global formal evaluation.

The **verification** process looks for the compliance of the first error: compliance of the specifications, ensure consistency and completeness and avoiding of redundancy. When the prototype of the system was already running, design specifications were tested; revised and new specifications were added to accomplish needs that were not initially known. For example, when we began the BIOMASS development, the Granollers WWTP only dealt with the suspended solids and organic matter removal, whilst, nowadays, the biological nitrogen removal has been implemented, so, the BIOMASS specifications were refined to cope with the N/D process. A consistent system behaves in a non-contradictory way. Normally this process is accomplished by the developer team (the expert and the knowledge engineer).

The **validation** process ensures that the system solves problems correctly, with adequacy (measures how much domain knowledge is covered by the system) and accuracy (related to the set of acceptable responses generated by the Supervisory System). Thus, in a knowledge-based system ensures the correct representation of the knowledge acquired. Therefore, this process deal with questions of correctness: *e.g.*, are the conclusions drawn by the system correct? Does the system fit well into the decision making process?…it depends on the internal reasoning of the system. For example, if an expert system cannot give the right responses, it means that the expert reasoning process was misinterpreted during knowledge acquisition. Validation should be conducted during development phase and also with the final prototype. One expects to get some level of acceptance performance in the early stages of the prototype development, which is expected to increase as the system development progresses. The expert(s) in the domain must conduct the validation process.

The third type of evaluation looks for the **usability** aspects of the system (interface, learning cost, documentation, subjective aspects…). Finally, the evaluation of **usefulness** looks for the improvements in the performance of the tasks of efficiency (productivity, response time) and effectiveness (reliability, availability) and in the system capabilities. The third and fourth types of evaluation cannot be evaluated until the user uses the software expertly.

Any evaluation process has three differentiated parts:

- Preparation of the evaluation: defining all the items that are part of an evaluation: the objective (why the evaluation is to be performed ? For example, to check the validity of a knowledge base), the criteria based on the objectives (what aspects or characteristics should be checked? *e.g.*, check the knowledge base for accuracy and adequacy), the tests or techniques to be performed (how the evaluation is going to be performed) and the reference standard (what standard is selected for comparison). This standard can be either decisions developed by human experts or previously known results.
- Evaluation performance: The test workload is performed and the criteria are judged and assessed one by one, detecting errors, checking system responses, comparing the system responses with standards for agreement (comparing with expert responses or known results), and interpreting of the feedback obtained. The result of the evaluation could be either a quantitative value or a qualitative value (good/bad, valid, satisfactory, accurate…). Several formal validation methods or techniques are used in the evaluation tests.
- Decision making on the basis of the result of the evaluation: The decision making as a result of the value obtained in the evaluation can be either to modify the system or to continue with construction.

Nowadays, evaluation is no longer said to be an independent phase in knowledge based-decision support systems construction (see Figure 40 where part of the evaluation, known as validation, was positioned as a phase). Instead, it is considered as a constant activity, ongoing throughout the entire development process. The evaluation process is explicitly incorporated into the development life-cycle of the DSS prototype. Thus, a certain amount of evaluation is naturally done as part of the system development, as it has already been shown in the chapter explaining the knowledge base and case-based system development.. Nevertheless, a formal evaluation of the Supervisory System should be done over and above the error elimination carried out during development.

Figure 40 Ancient view of validation

In the next section, the evaluation procedure (with the four types of evaluation and different validation techniques), as it was performed in our Supervisory System, is described. The main part of this evaluation as well as BIOMASS implementation are described in [Comas *et al.*, 2000b].

8.2 Procedure for BIOMASS evaluation

It is still difficult to plan, control and conduct the evaluation process because, except for a few exceptions [Juristo, 1997] and [Borenstein, 1998], there are no general frameworks to assist system builders in organising the evaluation process for KB-DSS. While several proposals for validating computer-based models and Expert Systems have been published, none are targeted to validate KB-DSS. The methodology used in this work is mainly based on the work of the two authors cited before [Juristo, 1997] and [Borenstein, 1998].

The methodology to evaluate BIOMASS was carried out through a two-stage procedure: *laboratory* testing (verification, validation and usability) and field testing (field validation and usefulness). The evaluation methodology can be further described as follows:

- *laboratory* testing for verification, validation and checking for usability of each module independently (numerical, rule-based and case-based): the first evaluation addresses the internal aspect of the system (verification), secondly, validation with test cases or comparison with experts responses are carried out and third, evaluation of usability for each one of the modules of the Supervisory System. The correctness, consistency, validity and usability of each one of the BIOMASS' modules can be tested and evaluated throughout the execution of series of experiments with different techniques: questionnaires and interviews, laboratory (prepared) test cases, historical cases with known solution, laboratory experiments in which the system output and solution were directly compared with an expert prediction and solution (user assessment), sensitivity analysis…Some of them are described in the next sections since they were used in BIOMASS evaluation. For example, the verification, validation and evaluation of usability processes of mathematical models (like those built with GPS) involves the execution of experiments with a set of cases whose results are precisely known. If the software produces the correct results for a given set of inputs, then it has correctly solved the case. If it continues for the entire set of test cases, then the software system can be considered valid. Specifically, the validation process of a model is called calibration. These processes are especially interesting to gather all the problems originated during implementation, as well as the opinion of the experts and users that will use the Supervisory System, for avoiding some of these problems in the process of generalising this system to any WWTP.

- field testing of the overall system: field validation of the overall developed system with actual real cases and evaluation of the usefulness. In the field tests experiments, we test the entire system within its real environment with real problem-types in order to detect errors and refine, re-design of some models, correct or extend the knowledge base or the case-library, if necessary, identify needs for interface re-designs…Field experiments are the most effective of all validity tests if the situations permit (sometimes can be quite expensive) [Borenstein, 1998]. The evaluation of usefulness is still on going since the system is still being field-validated for 6 months more.

This two-stage evaluation procedure occurs iteratively throughout the system development. The results from any stage (or sub-stage) may require changes (reformulations, redesign, and refinements) in the prototype. Whenever the prototype is modified or expanded, the system must be re-evaluated. So, the system evaluation is not a linear process but can be best described as a spiral.

The next sections describe each one of the sub-stages carried out to evaluate BIOMASS for supporting WWTP management and control: verification, validation and usability for each module and field testing of the overall system.

8.3 Verification

Verification is a demonstration of the **consistency** and **completeness** of a system. In other words, verification refers to building the system "right", that is, substantiating that the system correctly implements its specifications [González and Dankel, 1993].

In the verification process we must check for the system specifications, the consistency and the completeness of the system. Some important issues to be considered are: checking for compliance with the specifications required by the final users are, that the system could deal with qualitative variables and missing data, the use of modularity to allow work with CBS and ES individually or together, the user interface, real-time performance requirements, the system maintainability, and the appropriate security measure against unauthorised modifications of the KB. There were no problems when checking for consistency in the case-based system, because there cannot be semantic or syntactic errors in case-based reasoning system, as its representation formalism has not a strict syntax. When verifying an expert system, we must consider only the knowledge base since the developers have already verified the inference engine.

8.3.1 Checking for Consistency

To check for consistency and completeness in a rule-based system, that means, to check for syntactic and semantic errors developers induced, the rule base must be checked for the following rules:

- Redundant rules: *e.g.*

IF	Influent flow rate is high AND Influent SS is not high	THEN	Hydraulic Overloading is True
IF	Influent flow rate is high AND Influent SS is not high	THEN	Hydraulic Shock is True

- Conflicting rules: *e.g.*

IF	Influent flow rate is high AND Influent SS is not high	THEN	Hydraulic Shock is True
IF	Influent flow rate is high AND Influent SS is not high	THEN	Hydraulic Shock is False

- Subsumed rules: one rule is subsumed by another if it has more constraints in the premise while having identical solutions. In this example, rule 1 is subsumed by rule 2 because the former has one more constraint than the latter.

1	IF	Influent flow rate is high AND Influent SS is not high AND Vertical velocity is high	THEN	Hydraulic Overloading is True
2	IF	Influent flow rate is high AND Influent SS is not high	THEN	Hydraulic Overloading is True

- Unnecessary IF conditions : similar to subsumed rules.

IF	V30 is high AND SVI is high AND Filamentous presence is excessive	THEN	Filamentous Bulking is true
IF	V30 is not high AND SVI is high AND Filamentous presence is excessive	THEN	Filamentous Bulking is true

The premises of these rules are identical except one in each rule that contradicts. If the first premises of each rule are truly unnecessary, these two rules can be collapsed into the single rule:

IF	SVI is high AND Filamentous presence is excessive	THEN	Filamentous Bulking is true

- Circular rules: these rules lead to an *n* infinite loop of useless rule firings. In forward-chaining systems rarely check if rule conclusions have been previously derived.

IF	Influent flow rate is high AND Influent SS is not high	THEN	Hydraulic Shock is True
IF	Hydraulic Shock is True	THEN	Influent flow rate is high AND

			Influent SS is not high

8.3.2 Checking for Completeness

- Dead-end rules: those rules that have actions that do not affect any conclusions and are not used by other rules to generate any other conclusion.

IF	DO gauge reads normal	THEN	the DO level is normal

- Unreachable rules: those rules with a premise that will never be matched.

IF	V30 is very low AND Filamentous presence is excessive	THEN	Filamentous Proliferation is not true

- Missing rules: those rules characterised by facts that are not used within the inference process, and conclusions do not affect to any other rule or procedure.

There exist tools to perform automatically the verification process by comparing premises and conclusions of each rule individually with all the others, comparing premises of one rule with all the others, comparing conclusions of one rule with all the others and comparing all the premises with all the conclusions. We have preferred to do it manually and in co-operation with the expert.

8.4 Validation

The validation of each module of the Supervisory System for WWTP management adapts the following general framework for validation:

- selection of validation criteria: When a prototype makes a mistake, it will result in applying an inadequate solution to the current problem. This error may be due to deficiencies in **accuracy** (set of acceptable responses) and **adequacy** of the system to the domain knowledge covered. In other words, validation refers to building the "right" system, that is, substantiating that a system performs with an acceptable level of accuracy [González and Dankel, 1993]. The accuracy can be defined as the proportion of "acceptable" answers that a system generates (it can give us a quantitative measure by statistics). The adequacy measures how much domain knowledge is covered by the system. Generally, validation is more complicated than verification. A knowledge base of an expert system can be verified without being valid. A validated knowledge-based system ensures a correct representation of the knowledge and thus, correct solution to solve problems. The more common type of errors in representing the knowledge can be found among these three:
    - Errors of commission: a KBS arrives at an incorrect conclusion for a given set of input values. These errors affect the accuracy of the system. Easy to detect but often difficult to locate and correct.
    - Errors of omission: When a set of input values fails to cause the system to reach a conclusion. The knowledge necessary to solve a particular problem is not found in the KB. This error is more difficult

to detect and affect the adequacy of the system. The adequacy refers to how much of the problem domain is covered by the KBS.

- Control faults: Rules are correct but have undesirable control behaviour.

- selection of reference standard: When validating, we need to select reference standards or norms with which we can compare the actual behaviour of the system (to define the agreement of the system's results):
  - Compare against known results (historical or prepared cases): these test cases should be based on actual situations and should cover a range of levels of difficulty and test as many aspects of the system as possible. If prepared, they should be generated by unbiased experts.
  - Compare against human expert performance: norms prescribed by the experts for problem solving heuristics. They must be free of bias or prejudice.
  - Compare against theoretical norms: if the KBS is modelling a physical process.
  - Sensitivity analysis to input variations and to input errors.

- To run a set of experiments using different methodologies to test the prototype, obtain solutions, compare with experts, historical cases and calculate performance. Finally, a decision making on the basis of the validation results. This decision involves to carry out in the development phase or to modify or change some points of the evaluated system.

There are several methodologies, not mutually exclusive, but recommended to apply concurrently to provide depth as well as breadth within the validation effort. We have used some of them in the simulation model, the rule-based system, the CBS and finally, the entire system validation.

8.4.1 Classical control validation

The automatic DO controller installed in the plant has been validated in field-experiments (*in situ*). It has been proven to be an efficient way to maintain the desired DO levels in the activated sludge process and it has resulted in a significative reduction of the energy used in the aeration process with respect to the previous control (see section 4.1.5).

8.4.2 Simulation model Validation

As explained in section 7.6, the final validation of the mechanistic model implemented in GPS-X is still being carried out.

With respect to the black-box model, preliminary experiments with soft-computing techniques have enabled to find several acceptable sub-models based on heterogeneous neural networks for the Lloret WWTP, which perform statistically satisfactory and better than other well-established techniques. Several staged studies have been performed with historical cases as reference standards towards the development and evaluation of input-output behaviour models for the prediction of some variables for this WWTP. In order to evaluate the accuracy of these models, three experiments have been carried out. To this end, first of all, the time behaviour of two effluent variables (COD and BOD) was correctly captured and reproduced into an input-output behaviour model (experiments 1 and 2). The next natural step (experiment 3) was to take into account qualitative variables since they convey a great amount of information but usually put aside of the models because of its nature and high level of missing values [Capodaglio *et al*., 1991]. The experiments have been carried out with a database of 609 consecutive historical days which includes both quantitative (analytical results from water and sludge quality and on-line signals) and qualitative information (microscopic examinations and *in-situ* plant observations) with high incidence of missing values. In this section, these experiments are briefly discussed. The material presented has been published in [Belanche *et al*., 1999a] , [Belanche *et al*., 1999b] and [Belanche *et al*., 2000].

Experiment 1

In the first experiment performed, two techniques based on neural networks are employed: a heterogeneous neural network (trained with genetic algorithms, TDNN-HG) [Valdés and García, 1997] and a classical neural network (the multi-layer perceptron, trained with simulated annealing plus conjugate gradient, TDNN-AC). Both are used as *time-delay* neural networks. The reference standard used were historical cases

The linear intercorrelation structure among variables is shown in Figure 41 as an average clustering of the (absolute) correlation matrix of variables. With the exception of wasting flow rate, the action, effluent and influent variables were clustered into three groups. The high intercorrelation of effluent variables (0.75), indicates that once a reasonable model is found for one of them, similar ones should be also found easily for the rest.

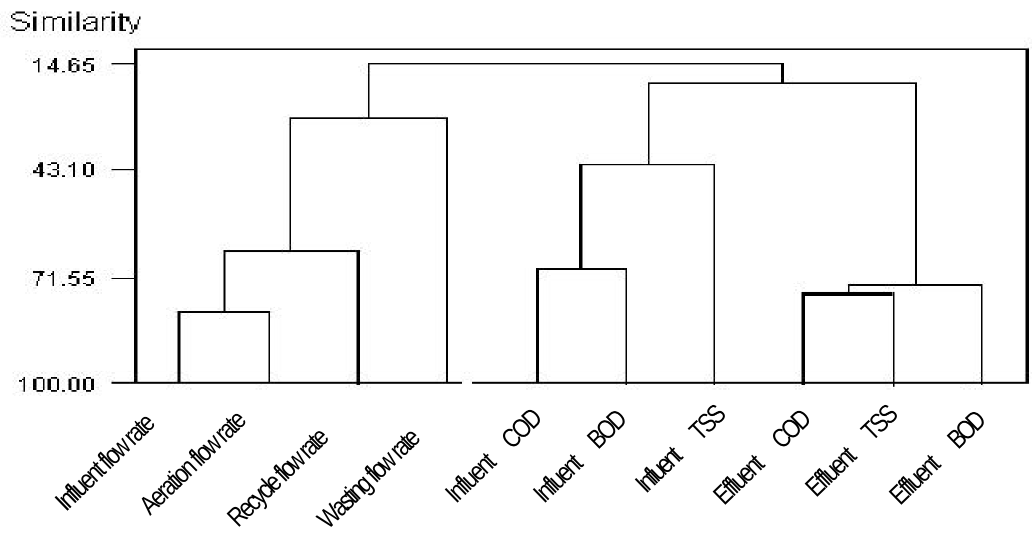

Figure 41 Average clustering of the absolute correlation for the studied WWTP variables

In this experiment, the time behaviour of effluent COD and BOD are modelled as a function of influent characteristics and control actions (only quantitative variables) by means of developing a model for each variable. The TDNN-HG and TDNN-AC architectures were fixed to include one output unit and 8 hidden units, corresponding to the model:

$$y(t+1) = F\{x(t), x(t-1), x(t-2), y(t-1)\}$$

where x(t) denotes the current value of the input variable and y(t) denotes the value of the output. Selected input variables were influent flow rate and the three action variables (aeration, wasting and recycle flow rates). Hence, the model is composed of a total of 13 inputs. According to the results, the characterisation of effluent COD and BOD via classical Neural Network was worse than the corresponding one obtained by using a fuzzy heterogeneous Neural Network (see Table 17).

	TDNN-AC	TDNN-HG
effluent-BOD	45.55%	20.74%
effluent-COD	30.76%	11.64%

Table 17 Results of NN models when predicting effluent BOD and COD

The corresponding time behaviour is illustrated in Figure 42, where the observed effluent BOD values are displayed together with the 95% confidence band given by the neural network model (upper and lower dashed curves).

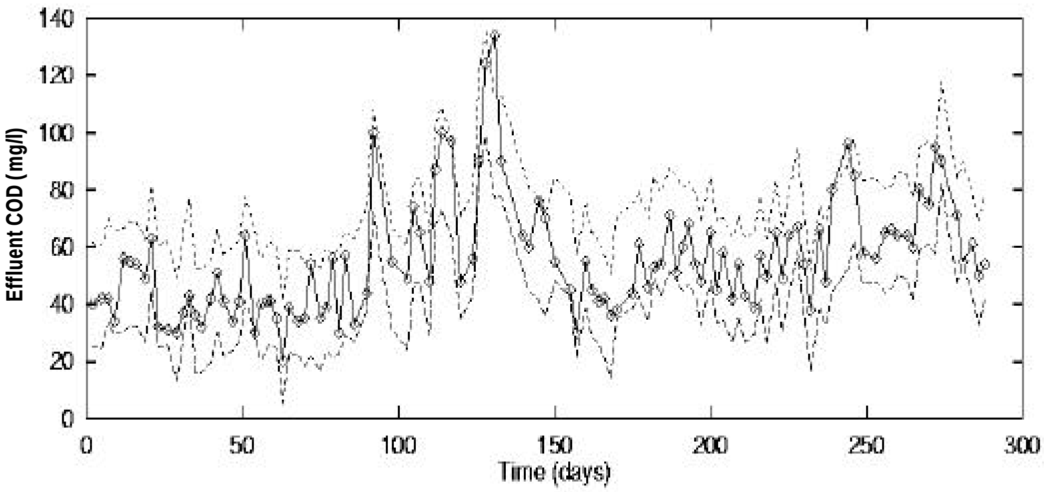

Figure 42 Time behaviour of effluent COD during the first 300 days (solid line) with observed points. Upper and lower dashed lines indicate the 95% confidence estimation interval (according to the TDNN-HG model).

Experiment 2

The next step was to develop a model able to predict future WWTP effluent COD in situations never seen before (that is, not used in the formation of the model) again in light of available past values of its variables. We selected influent, recycle and wasting flow rates, influent COD and TSS and the target variable effluent COD itself (of previous days) as input variables to predict effluent COD, according to reasonable similarity of the groups (influent, aeration and recycle flow rate), (influent COD and BOD) and (effluent COD, BOD and TSS) as shown by the correlation structure reflected in Figure 41. Besides, we observed that part of the errors of the models inferred in the previous experiments were due to the high peaks present in both studied variables (effluent COD and BOD). For this reason, effluent COD was $\log_{10}$ transformed.

In the present study an experiment was made by forming a data matrix containing the information concerning the behaviour for each day of the last 10 days for the six selected variables. This makes a total of 60 new variables potentially related with the value of the effluent-COD for each day, Some experiments with rough sets were carried out to find significant time delays for each variable. The final selected variables and delays were : Influent flow rate (delays 1, 5, 10), influent COD (delays 5, 7), influent TSS (delay 7), recycle flow rate (delays 1, 2, 3, 4, 5, 7, 9, 10), wasting flow rate (delay 5) and $\log_{10}$(effluent COD) (delays 2, 3, 5, 7). This delay information was used to set up a prediction model based on a fuzzy Heterogeneous Neural Network (HNN) as in Experiment 1, this time with effluent COD with delay 0 as target. A very simple HNN architecture consisting of just 2 neurons was utilised (20 inputs, 1 output), with the same training set used for the previous experiments (50% of the total available). The last 25% (56 days) as data to be predicted. Also (like in experiment 1), very prudent training settings were used to avoid excessive data over fitting.

The HNN model, although far from perfect, does capture prediction information and is able to prognose effluent COD within a 95% confidence band. This is also particularly important having into account the WWTP complexity and the big quantity of missing information spread in the available data set.
For more information about experiment 1 and 2 refer to [Belanche *et al.*, 1999b].

The next natural step is to take into account qualitative variables and to explore how it affects the formation of these predictive models. This qualitative information, although known to exert an influence in the process and conveying a great amount of information, is usually put aside because of its nature and the high levels of missing values that it brings along. These two features are a nuisance - if not a problem - for many neural learning algorithms and models, which have to accommodate qualitative and missing information in a deformative pre-processing.

Experiment 3

In the third investigation, we performed several experiments using qualitative information, either per se or together with quantitative information, such as influent characteristics and control actions. Specifically, the influence of qualitative variables on predicting effluent TSS levels is studied, as an indication of plant performance and fulfilment of regulations. Thus, a model for predicting effluent TSS was studied in order to find a reliable model for predicting the bulking phenomenon. Rough set theory was applied to reduce the number of input model variables.

In these studies, classical time-delay neural networks (the multi-layer perceptron, trained with simulated annealing plus conjugate gradient, TDMLP) and heterogeneous time-delay neural networks (trained with genetic algorithms, TDHNN) were used and compared with probabilistic (trained as a Bayes-Parzen classifier, TDPNN) [Specht, 1990] and the k-nearest neighbours algorithm (*k*-NN). Rough set theory was also used to perform a reduction of dimension [Pawlak, 1991].

Four architectures formed by a hidden layer of 2, 4, 6 and 8 neurons and an output layer of a linear neuron were studied. The general model was :

$$y(t) = F\{x_1(t-2), x_1(t-1), \ldots, x_m(t-2), x_m(t-1), y(t-2), y(t-1)\} \quad \text{for } \forall\ t \geq 3$$

where *m* is the number of input variables, for a total of 2*m*+2 model input variables. Each $x_i(t)$ denotes the value of the *i*th input variable and y(t) the value of the target output variable (effluent COD, BOD or TSS), at time *t*. The number *m* varies and will be specified accordingly. Despite the high levels of missing information, very reasonable prediction models are found (see Table 18)

Experiment			TDHNN		Classic (TDMLP)		TDPNN	*k*-NN
			best	avg.	best	avg.	-	-
3A	Qualitative (38 input var)	train	87.0%	82.2%	86.9%	82.2%	76.5%	-
		test	80.0%	76.3%	73.3%	47.5%	73.3%	76.7%
3B	Reduced-qualitative (12 input var)	train	85.2%	81.5%	82.6%	81.3%	83.5%	-
		test	76.7%	75.4%	76.7%	70.2%	16.7%	73.3%
3C	Combined (48 var)	train	84.3%	81.7%	81.7%	80.6%	100%	-
		test	75.6%	73.2%	70.7%	70.2%	70.7%	61.0%
3D	Reduced-combined (13)	train	83.8%	81.2%	80.6%	78.3%	100%	-
		test	73.2%	71.6%	70.7%	70.1%	70.7%	63.4%

Table 18 Results of TDNN models and *k*-NN algorithm

Experiment 3A: Oriented to reveal the influence of qualitative variables when studied per se; There were 38 input variables (18*2 + 2). The results are quite similar and consistent both for training and test sets. In other words, no method clearly outperforms the rest. Second, there seems to be a limit in training set accuracy around 87.0% and at 80.0% in test, which is a not so bad result for such messy data. Also interesting to note are the solid results achieved by the TDHNN , the poor average achieved by the TDMLP and the comparatively good *k*-NN performance.

Experiment 3B: In order to assess the viability of smaller models, a new data matrix was constructed, as a result of reduction with rough sets, with 12 variables :

Variable	Presence-foam	Effluent-appearance	*Zooglea*	*Nocardia*	*Thiothrix*	Type 0041	*M.Parvicella*	Carniorous ciliates	*Rotifer*	*Aspidisca*	Effluent-TSS	Effluent-TSS
Delay	*t*-2	*t*-2	*t*-2	*t*-2	*t*-2	*t*-2	*t*-2	*t*-2	*t*-2	*t*-1	*t*-2	*t*-1

Table 19 Reduced set of qualitative variables for experiment 3B

Selected variables include all the filamentous bacteria - dominant in situations regarding poor sludge settleability, making solids more likely to escape the settler -, and also the presence of the predicted variable in the two previous days. Moreover, and due to the frequency of analysis and observations, the 2-day lag variables dominate over 1-day ones, a consistent result.

The predictive accuracy of the classical and heterogeneous neural architectures still keep a decent classification ability, slightly above the 73.3% limit imposed by the major class. Moreover, the results are quite balanced between the training and test sets, and what is more important, almost identical with respect to those obtained for the model having all qualitative variables, thus showing that a shorter model with only less than one third of the original variables says the same about effluent-TSS than the whole set.

Experiment 3C: Aims at discovering how qualitative information behaves when joined to five selected quantitative variables: those corresponding to inflow characteristics (Influent flow rate, influent COD and TSS) and control actions (wasting and recycle flow rates). Total input variables are 48 (23*2 + 2).

Experiment 3D: The model of experiment 3C is reduced.

Variable	Influent flowrate	Influent flowrate	Influent COD	Influent TSS	Recycle	Recycle	Wasting	Wasting	*Nocardia*	*Aspidisca*	*Thitothrix*	Effluent-TSS	Effluent-TSS
Delay	*t*-2	*t*-1	*t*-2	*t*-2	*t*-2	*t*-1	*t*-2	*t*-1	*t*-2	*t*-1	*t*-2	*t*-2	*t*-1

Table 20 Reduced set of *combined* variables

This reduced set gives much information: first, numerical variables are predominant, despite their lower number with respect to the qualitative ones. Among them, the physico-chemical inflow characteristics (Influent flow rate, influent COD and TSS) and the control actions (wasting and recycle flow rates). Second, we can see how this information is needed at both delays for the inflow rate and the control actions. Third, the three qualitative variables include the most commonly filamentous bacteria found in this plant (*Nocardia* and *Thiothrix* or type 021N) causing bulking sludge, and a protozoa (*Aspidisca*) whose absence may indicate a decrease in plant performance and poor settling characteristics. It is also remarkable the fact that these three variables also appeared in the previous reduced set of qualitative information, and are the sole survivors when mixed with the numerical information. The behaviour of this model is similar to that of the previous, in the sense that classification performances for training and test sets are slightly less, showing that the effect of the 35 discarded variables was in fact small. the fact that the TDHNN model gives slightly but consistently higher results and a more balanced training/test ratio than all of the other methods can be attributed to its better treatment of missing values and qualitative information.

Summarising the results, it was found that qualitative information exerts a considerable influence on plant output, although very unevenly. A high degree of information redundancy was discovered, since comparable predictive capabilities of effluent TSS are obtained when working with a much more reduced set of variables, which coincide with those highly rated by WWTP experts. For qualitative variables only, it signals the greater importance of 2-day delayed data in the process dynamics, as opposed to 1-day data. When qualitative and numerical information are collectively considered, the latter are found to be amongst the more informative, always in both delays. In both cases, these selected variables are also highly rated by WWTP experts. They also tend to be the ones with less amount of missing values, thus reducing the relative overall amount.

In addition, common upper-bound in classification accuracy is discovered, located around 87% accuracy in the model search process (the training) and an 80% of predictive accuracy (that is, using the learned model), which is a very nice result for such messy data. In this respect, it is our conclusion that the generalised and (relatively) poor performance can be attributed almost entirely to the data - besides, of course, to the problem complexity - in light of the consistent results yielded by methods that are so different in nature. The possibilities of these methods are also noteworthy, provided they can handle heterogeneity, imprecision and missing values, aspects that characterise the data in a WWTP process. For further information about experiment 3 refer to [Belanche *et al.*, 2000].

The long-term aim of this work of finding a reliable model is still under current research and development. The immediate future work to be done is oriented to add information in the form of better delays periods (*i.e.* the discovery of those time delays in the input variables and in the predicted variable itself carrying essential functional relationship, *e.g.*, the weekly effect) and a more accurate selection of variables, always taking into account the findings reported herein. Ulterior studies with data coming from other plants will be needed to determine whether these patterns are specific or else they represent a more general property of WWTP. A further goal in the future is the development of a predictive model for control variables (wasting and recycle rates). These models will altogether supply the plant manager with a useful tool to improve plant control and operation.

8.4.3 CBS validation

An error in the CBS may be due to a small case-library (insufficient adequacy, *i.e.*, insufficient representation of the WWTP domain), a faulty retrieval mechanism (the most similar case is not retrieved) or a faulty adaptation mechanism. Therefore, **accuracy** (set of acceptable responses) and **adequacy** to the domain knowledge covered are the validation criteria selected.

We have combined methods involving the expert responses, laboratory (prepared by the expert) test cases and a method adapted from [González *et al.*, 1998], which uses a subset of historical cases with known solution from the own case-library, as reference standard, minimising the need for intensive expert involvement. Methods requiring a complex validation model (which can predict the performance of CBS under certain pre-selected conditions) have been avoided for the extensive effort to derive the mathematical method.

The set of test cases must be designed and generated. Experts must be asked for the needs of generate additional test cases representing gaps in the set of cases already presented (attempt to eliminate errors of omission). Then, the CBS is tested over this set of cases and a decision is taken on the basis of the validation results. The CBS prototype should correctly solve almost all test cases. We compare each case tested with the most similar case retrieved. If CBS responses differ from expert responses or known solution (*i.e.* we retrieve a case with a different diagnosis from the actual case as the most similar), the overall accuracy of the system is under the pre-established minimum value or any other error is detected, the system must be corrected/changed/altered/extended.

If CBS fails, each variable of actual and most similar retrieved case are compared and the trace followed by the new case through the hierarchical memory is checked trying to identify where is the problem. The corrective actions taken to refine the CBS prototype included:

- modification and adjustment of the weight assigned to each variable: if we retrieve the correct answer but it is not the most similar (distance too high).
- modification of the discrimination order: Sometimes results impossible to reach optimal cases because is exploring a wrong area of the hierarchy.
- modification of the discretised modalities: if the best or correct answer does not appear among the retrieved cases.
- To add or remove some variables in the case definition: *i.e.* the expert decide to remove BOD because its analysis lasts 5 days and in fact, it can be estimated from COD. On the other hand, he decides to include two qualitative variables: The predominant filamentous organism and the qualitative observations in the V30-settling test.
- Modification of the maximum and minimum values of each variable

According to the CBS and field validation results, these corrective actions were implemented several times in an iterative process with the continuous expert supervision until obtaining a case definition (with the most relevant variables) and a case-library (with the more proper weight assignment in flat memory, as well as the optimal discriminate order and discretised variables in hierarchical memory) that perform with acceptable accuracies and adequacy.

Next sections present the four tests carried out to validate the CBS module individually. Three of them were focused to validate the accuracy of different issues of the retrieval phase: one for validating the **structure implemented** and indexing method (plain and hierarchical memory), one for validating the accuracy of the **similarity measurement** used, and one for validating the accuracy of **using meta-libraries** in the retrieval phase instead of the standard retrieval (only one discrimination tree). These three experiments are intended to improve the effectiveness and efficiency of case retrieval. Finally, a domain coverage test was performed to validate the **adequacy** of the system. The results presented correspond to previous validations of the CBS conducted before the Granollers WWTP implementation. Therefore, these experiments were carried out for the CBS validation of previously studied WWTPs (Girona and Lloret).

It is not necessary to validate the adaptation phase in our CBS prototype since the solution of the most similar case needs no adaptation to directly being applied to the actual case or, at most, sometimes involves a simple parameter adjustment algorithm, under the assumption that the distance between the case retrieved from the library and the current case is small enough that only a linear interpolation adjustment of the parameter involved in the solution is needed.

8.4.3.1 Test 1: Validation of structure implemented

Two experiments were carried out to validate the case indexing method. In both cases, the validation criterion is the accuracy (set of acceptable responses) and a set of test cases has been selected from the historical database to run the experiments. Differences between both experiments are due to the reference standard used and the running technique involved. In the first case, human experience was used to compare and the running test was based on a ten-fold stratified cross-validation. In the second experiment, historical cases with known solution were used as standard and an adaptation from [González *et al.*, 1998] as validation technique.

Experiment 1

The CBS is exposed to historical cases (with unknown solution), they are processed by the retrieval algorithm and the answers are compared for agreement with those of an expert who try to solve the same problem. Yes or no, or agree or disagree can be possible agreement degrees. To estimate the accuracy of the case retrieval step on unseen cases for different case-library structures, we performed a ten-fold stratified cross-validation. A whole set of 243 examples was split into 10 sets of 24/25 examples each: these were in turn used as test sets, while the remaining 219/218 examples were used for training.

In the WWTP domain utilised in [Comas *et al*., 2000a], the case was codified through the 19-most relevant variables measured routinely in the plant according to the expert criteria. Three kind of structures were tested:

- a plain memory (similar to *k*-NN algorithm),
- a hierarchical case-library but only learning the relevant cases according to a defined relevance criterion (sustainable learning), and,
- a hierarchical case-library learning all cases of the training set (complete learning).

Finally, a fourth test was carried out in order to compare the plain memory using only the most relevant 19 attributes with respect to the plain memory using 63 attributes to define each case.

After the 10-fold cross validation in the data set, the average predictive accuracies for each kind of test are detailed in the Table 21. The criteria used by the experts to validate the obtained results were to compute the percentage of times that the optimal case was retrieved in first position [Veale and Keane, 1997]. The predictive accuracies of the experiments were measured not only for the most similar case, but also for the second more similar case and for the predominant (majority vote) of the retrieved cases.

Type of library		plain memory	hierarchical	hierarchical	plain memory
Number of Examples used		243	220 (relevant cases)	243 (all cases)	243
Number of Attributes used		19	19	19	63
Case Retrieval Accuracy (%)	First	65.8	62.50	64.20	68.7
	Second	59.7	44.9	44.4	60.5
	Predominant	68.73	52.3	51.1	70.40

Table 21 Case-based learning results

Different relevant outcomes can be extracted from these results:

- All types of library get better accuracies for the retrieved case in first position except for plain memory that has higher accuracy for the predominant case. The loss of accuracy for predominant case is due to the retrieving of examples of large classes when dealing with a case belonging to a small class.
- Both hierarchical libraries underwent only a little loss of accuracy (3.3 and 1.6%, respectively) with respect to a plain memory library while a big improvement in time retrieving is achieved.
- The performance of the selective learning algorithm of the CBS has turned out to be very good since the accuracy of the hierarchical library with only relevant cases (sustainable learning) is very similar to the hierarchical library with all the cases (complete learning).
- The loss of accuracy using 19 or 63 attributes is minimal (less than 3% and 2% in the first and predominant case retrieved, respectively) whereas there is a great gain in time retrieving.

Experiment 2

One problem with this approach is bias or subjectivity introduced by the experts or developers. It is very important to maintain objectivity during validation task. A way to eliminate bias is the CBS retrieval test proposed in [González *et al.*, 1998]. This paper proposes a method that minimises the need for intensive WWTP expert involvement in the validation process. This method uses the cases with known solution from the system's own case-library. This retrieval test requires that each historical case in the case-library "spawn" a test case identical to itself. Each test case generated is presented to the CBS as the current case. The CBS system goes through the comparison and retrieval processes, arriving at an internal list of library-cases ranked in decreasing order of similarity. In order for any case test to be marked as successfully executed, the historical case that spawned the current test case should be found as the top-ranked historical case in the internal list (the similarity distance should be the minimum). This process is repeated for each case in the test-case list. In other words, this method uses the same whole set of examples (243) for training and test sets and calculate the percent accuracy or retrieval success rate (Table 22).

Although use of experts is minimised, it is needed to a small degree in determining the minimum system validity criteria to determine whether, in light of the executed and evaluated suite of test cases, the system can be considered valid. If the retrieval success rate is greater than the minimum system validity criteria (in our case, it is defined to be 85%), the retrieval phase is considered to be valid.

Type of library	plain memory	hierarchical	hierarchical	plain memory
Number of Examples used	243	220 (relevant cases)	243 (all cases)	243
Number of Attributes used	19	19	19	63
Case Retrieval Accuracy on whole data set (%)	100	97.1	98.8	100

Table 22 Results of the case retrieval test performed over the CBS prototype.

Comparison of CBS with other machine learning methods

A comparison between Case-based learning system and three more machine learning methods (C4.5, CN2 and *k*-Nearest Neighbour algorithm, *k*-NN with *k*=4) was conducted for WWTP data classification in [Comas *et al.*, 2000a]. C4.5 and CN2 techniques have already been introduced in chapter 5 and the *k*-NN algorithm in this chapter above. This paper presents the application of these four different machine-learning techniques to the task of classifying 243 descriptions with 63 variables of the daily operation of a Wastewater Treatment Plant into 20 different classes. The classes (state of the process) for each case had previously been obtained by clustering (test case with known solution) [Comas *et al.*, 1999]. The four approaches were compared in terms of predictive accuracy after a 10-cross fold validation and in terms of understandability of the induced rules/patterns. A summary of the comparison is given in Table 23.

Method	Number of Examples used	Number of Attributes used	Prediction accuracy on test set (%)	Prediction accuracy on whole data set (%)	Meaningful Interpretation
C4.5 (63 attributes)	243	24	63.51	89.7	Partially
CN2 (63 attributes)	243	44	63.98	98.8	Partially
k-NN (63 attributes)	243	63	76.38	100	No
C4.5 (19 attributes)	243	11	65.11	87.2	Mostly
CN2 (19 attributes)	243	19	65.45	95.9	Mostly
k-NN (19 attributes)	243	19	71.22	100	No
CBS (plain memory)	243	19	68.73	100	No
CBS (hierarchical, relevant cases)	220	19	62.50	97.1	Yes
CBS (hierarchical, all cases)	243	19	64.20	98.8	Yes
CBS (plain memory)	243	63	70.40	100	No

Table 23 Comparison of the four methods.

Best accuracy was obtained with the *k*-NN method. This could be expected, since the clustering used to design the classes was basically performed with Linneo+, which itself is based on the notion of distance. The main problem of *k*-NN methods is the expensive time requirements. In contrast, the retrieving process in a hierarchical case-library induced by the CBS or in an induced decision tree by C4.5 is very fast since only few branches of the hierarchical trees are explored by the algorithm search. The loss of accuracy of the CBS using only the 19 attributes selected by the expert with respect to *k*-NN methods can be estimated about 10% while the number of variables is reduced from 63 to 19 (more than 69%). In comparison to the C4.5-trees and CN2-rules induced by using all 63 attributes, the CBS with plain or hierarchical library (with complete learning) appears to be slightly more accurate. For a more complete comparison, the *k*-NN, C4.5 and CN2 techniques were also tested on the 19 expert selected attributes. *k*-NN performance drops significantly (as compared to 63 attributes), but is still better than the CBS. The performance of C4.5 and CN2 in terms of accuracy improves slightly. More importantly, the understandability of the induced trees and rules improves greatly, making them much more acceptable for use in a knowledge-based system (usability).

8.4.3.2 Test 2: Validation of similarity measurement

Another issue of the case retrieval validation is the validation of the similarity measurement developed and used by our research group (*L'Eixample*). In [Sànchez-Marrè *et al.*, 1998], a set of 10 historical test cases were used to evaluate *L'Eixample* distance with respect to other similarity measures for case retrieval in a CBS. The retrieval tests were conducted with two different WWTPs (one with qualitative and non-ordered categorical attributes and the other one only with ordered quantitative attributes). In these experiments, the experts used two evaluation criteria: the first one was to compute the percentage of times that the optimal case was retrieved using a concrete similarity measure [Veale and Keane, 1997]. The results are shown in the Table 24.

Similarity Measure	% Optimal retrieval Lloret WWTP	% Optimal retrieval Girona WWTP
Discrete Manhattan (MD)	60	60
Discrete Euclidean (ED)	80	60
Discrete Exponential-weighted Manhattan (EMD)	80	70
Continuous Manhattan (MC)	50	90
Continuous Euclidean (EC)	60	80
Continuous Exponential-weighted Manhattan (EMC)	60	70
Weight-sensitive Manhattan (MW)	60	90
Weight-sensitive Euclidean (EW)	80	90
Weight-sensitive Exponential-weighted Manhattan (EIX)	80	90

Table 24 Percentage of optimal retrieval in both domains

From the performed experiments and from Table 24, it can be observed that in the Girona WWTP [1] the discrete distances are worse than the continuous, and these are worse than the weight-sensitive distances. But in the Lloret WWTP [2] happens the opposed fact. We think that this is due to the fact that in Girona WWTP there are only ordered continuous attributes while in the other domain, there are some important non-ordered categorical attributes. At a first look, the *Eixample* distance –Weight-sensitive Exponential-weighted Manhattan– seems not to substantially improve the other weight-sensitive distances, but another deeper and more accurate study must be done to extract some conclusions.

A second criterion, considered by the experts as much important as the first one and recognised by some researchers as [An *et al*., 1997], was to consider not only if the optimal case has been retrieved, but also if the retrieval ranking and distance evaluation of the other retrieved cases are as good as expected. In Figure 43 there are the comparative results in the first domain [1] after retrieving the most similar cases for a concrete input case. The results are the computed distances, using all the similarity measures, for the first three more similar cases.

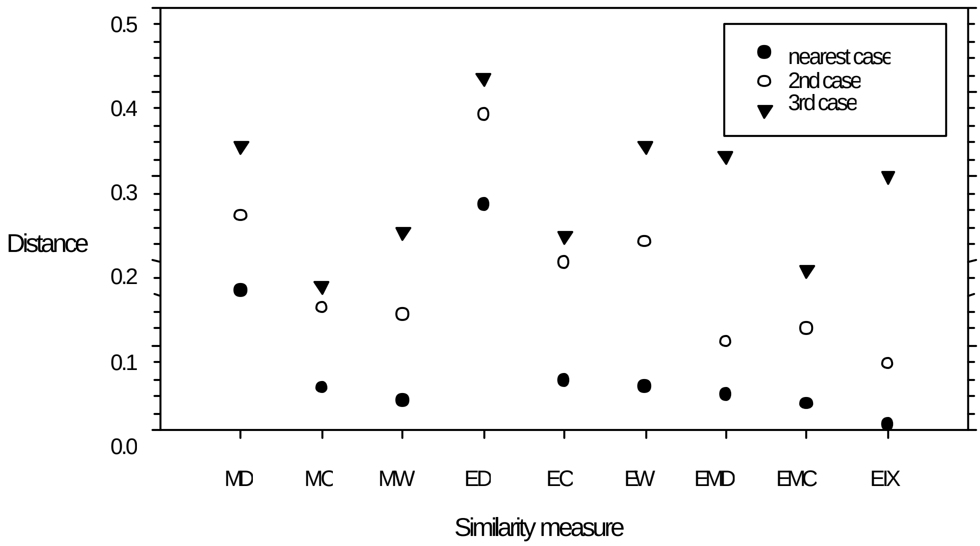

Figure 43 Optimal retrieval ranking in Girona WWTP.

Figure 43 outlines that *L'Eixample* distance really is the best measure, because the optimal case and the second nearest case are assessed as the most similar to the input case while the other distances are not as good as it. On the other hand, the experts have signalled the third case, as a very different case from the input one, and *L'Eixample* distance is one of the best measures in distinguishing that case. Other conclusions can be stated from these figures and other experiments done. The continuous distances are not as good as it seemed from the comparison of the optimal retrieval percentages, because they cannot easily distinguish the worse cases from the optimal ones. Continuous distances are best suited for domains, such in [1], described with many ordered quantitative attributes. Also, the Euclidean distances are best suited for domains, suc h in [1], having zero or few non-ordered categorical attributes, while the Manhattan distances are best suited for domains, such in [2], having more non-ordered categorical attributes. Therefore, *L'Eixample* distance derived from Manhattan distance, and combining discrete and continuous assessing of one-dimensional matching between attributes gets an improved performance for case retrieval.

8.4.3.3 Test 3: Validation of using meta-libraries

Another experiment was conducted to evaluate accuracy and reliability of using meta-libraries and meta-cases instead of a single hierarchical case-library. In the meta-cases approach, the case-library is splinted into a set of different smaller case libraries. Thus, the retrieval process starts matching the current case against a set of prototype cases, called meta-cases, to select one or more case libraries to search in. This approach tries to build several hierarchical organisations for different kind of cases.

This experiment was carried out using human experience as reference standard and a set of test set composed by 25 cases. The experts selected some cases from real data and others were designed and hand-written by the experts. As it was desired to test the new approach in hard conditions, it can be said that the test set is considered as a difficult one by the experts. For evaluation purposes, the same test set of cases was used for both cases, using both a sole hierarchical library and using meta-libraries. The criteria used by the experts to validate the obtained results was to compute the percentage of times that the optimal case was retrieved [Veale and Keane, 1997], in first position and in other positions within the retrieved cases list, using the same similarity measure previously used with the meta-cases assessment.

Optimal case retrieval	**Standard Retrieval (1 library)**	**Meta-cases retrieval (Libraries set)**					
		Standard	**Underloading**	**Overloading**	**Poor sludge settleability**	**Turbidity**	**Total**
First (%)	21	75	71	100	29	75	68
Other (%)	54	100	86	100	100	100	93

Table 25 Percentage of optimal case retrieval in both experiments

Table 25 shows the results obtained. From the performed experiments and from Table 25, it can be outlined that the "meta-approach", with several case libraries, seems to be more accurate and reliable than the standard approach, with only one library. The percentages of the optimal retrieval, both in the first or other position, are higher in the meta-cases retrieval than in the standard approach. The low percentages for the standard retrieval procedure are due to the hardness of the training set, as previously commented. This high percentages with the meta-case retrieval approach, seems to point out that the idea of working with different prototypes of cases, namely meta-cases, with different features and different feature ordering seems to be a good one.

Although, the "meta-approach" reached a better performance, by the moment, the real implementation of the CBS is based in a sole hierarchical case-library or a plain memory case-library.

8.4.3.4 Test 4: Validation of the CBS adequacy

In order to check the adequacy of the CBS, an adaptation of the Domain Coverage Test proposed in [González *et al.*, 1998] was performed. This test addresses the issue of how well the case-library covers all possible situations lived by the plant by an initial seed extracted from historical cases as well as evaluates the effect of the size. Since the size of the case-library grows as it learns, it is a direct measure of the system's domain coverage.

In this test, the case base library is broken down into three groups of test cases: Those corresponding to the first 50, 100 and 218 cases. The average relative error for each of the test case sets outputs that, with the growth in size of the running-case-library through the transfer of cases from the test case list, the average accuracy of the CBS increases (the average relative error decreases), from an initially unacceptable value of 38.9%, to one that became acceptable (64.2%). Table 26 shows the results of the test series for the domain coverage test.

Test #	Running-Case-library (number of examples)	Test-Case Set (number of examples)	Prediction accuracy on test set (%)
1	50	193	38.9
2	100	143	42.7
3	218	25	64.2

Table 26 Test series for the domain coverage test.

In views of these results, it is advisable that case-library should learn more and more cases to increase the performance of the system unless the relevance criterion does not indicate the opposite.

8.4.4 Rule-based system validation

Different approaches exist for validating rule-based systems. Among them, face validation and historical test cases (in which the results are known) techniques were combined to check for the accuracy and adequacy of the knowledge base of the rule-based or expert system. The criteria of the plant manager were used as reference standard. The methodology utilised to discover inaccuracy and inadequacy in the ES knowledge base was the following:

1. Test the rule-based system with historical real cases (historical **test cases**). Every time the expert system was activated, it reached a diagnosis following a specific reasoning path of one of the developed decision trees.

2. Make a meeting between one or more experts to discuss in a superficial and qualitative way each conclusion reached by the system (**face validation**). Compare the system diagnosis with the real state of the plant of that day. While this technique can be useful as the first approach, it cannot be considered satisfactory as the sole means of validating an ES. The reasoning path followed by the ES was compared and discussed with the expert of the plant. The application of a questionnaire to the expert helps to collect information to support this process. Main topics of the questionnaire were:
   - i. the situation analysed is correctly identified ?
   - ii. the inference followed corresponds to the expert heuristics ?
   - iii. decision variables and their values are appropriate ?
   - iv. does the system right detect the cause ?
   - v. do you think that the solution derived is credible enough ?
   - vi. how do you think it is possible to improve the expert system ?
   - vii. list advantages and disadvantages of using the expert system
   - viii. evaluate the overall performance of the expert system as very good, good, fair or poor.

Next steps are focused in the concrete detection of incorrect paths in each one of the decision trees:

3. Identify and register which problems have been well diagnosed, which have not and which others have been not detected. In a similar way, identify the causes detected and the actuation proposed.

4. Identify and register the abnormal qualitative values (very low, low, normal, high or very high) of the variables that have launched the intermediate alarms of the explored problems (the symptoms).

5. For each problem diagnosed by the ES (*i.e.* for each decision tree explored), identify the traces followed by the expert system (rule trace validation method) to infer the situations detected, it means, to identify the branches of the decision trees explored.

6. According to sections 4 and 5, underline the symptoms and the traces followed by the ES over a paper representation of the decision tree explored. This paper representation makes the plant manager easier to identify the correct or incorrect inference paths followed. Bold branches of Figure 44 show the symptoms and the rules traced by the ES when diagnosing a situation of loss of nitrification caused by limiting temperature.

7. Show these representations to the expert criteria that compare the traces with his problem-solving strategies. This comparison enable us to discover which of the rules have been correctly fired and which did not and in which sequence, and find errors of commission or omission. These errors can be in the

symptoms that alarm for a possible problem, in the reasoning process followed by the expert system or/and in the conclusions reached.

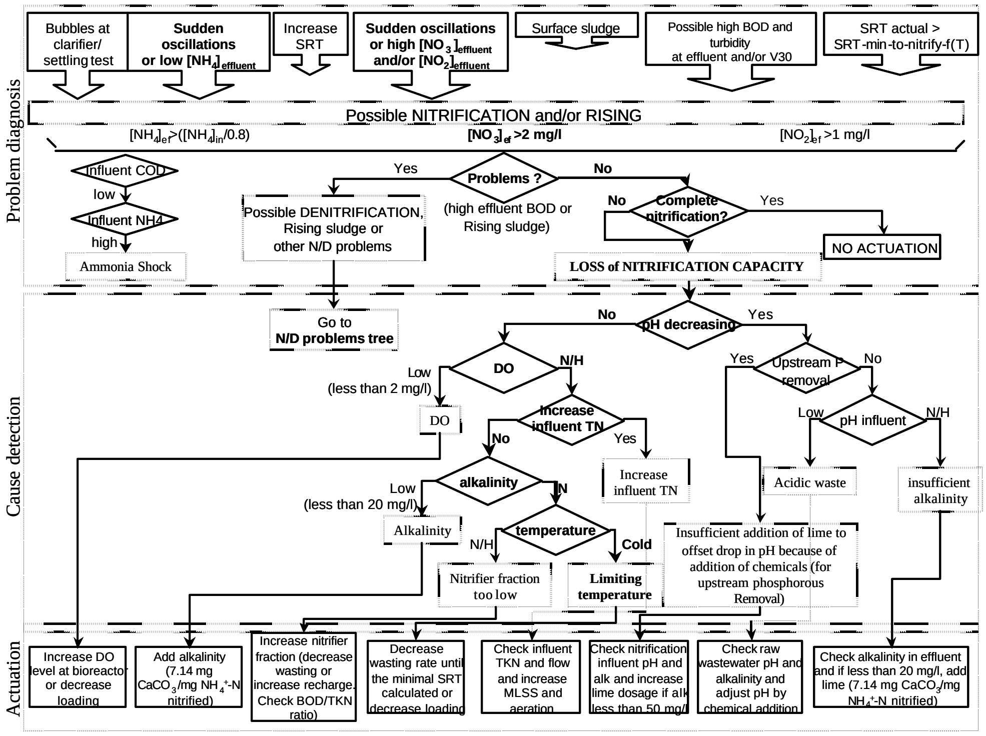

Figure 44 Loss of nitrification due to low temperature in the N/D decision tree

8. The rule-based system validation permitted system refinement and further expansion to reflect better the experts' solution procedures. As a result, during this period, new rules, procedures or facts are added whilst other are modified or deleted (rule refinement, reformulation and revision). The modifications made in the knowledge base during the expert system validation include:
   - changes in meta-rules
   - addition of some causes of problems previously not considered
   - adaptation of the general actions proposed to the specifications of the studied plant
   - changes in the modalities of each variable (low/normal/high)
   - addition of some problem-solving strategy previously not considered
   - modification of the reasoning path of some problem
   - detection of inference paths with lack of values of some variables
   - discovering of some situation not covered by the expert system

and other more specific aspects:

- detection of values that expire before they were expected to
- verification of the need of checking some other fact before inferring clearly a problem (discard other problems)
- detection of errors in data abstraction

- detection of errors in calculating trends of data
- detection of errors in formulas
- verification of the need for obtaining systematically the qualitative observations from operators
- to detect when there is an unexpected shutdown of the system, *i.e.*, when an electrical cut succeeds
- to detect when the blowers have been stopped during many hours

9. Ask to the expert for possible domain knowledge not covered by the system (adequacy).

We have modified several rules and procedures in about 30 times of applying this checking methodology. Concrete values for rule-based system accuracies were obtained during the field-test validation (section 8.5).

8.4.5 Evaluation of Usability

This step evaluates the ease of use of the system. The user gives his/her opinion on each usability criteria: interface, user load, fitness for task, compliance with standards, learning, documentation, subjectivity, etc…The applied technique was to submit each module to tests with different scenarios and collect the user's opinion through face-to-face conversations or application of questionnaires. Some modifications as a result of the responses of a panel of experts include: interface modifications, graphical amendments, adaptation of the way to inform about the diagnosis of the process state, changes in the documentation supplied and in the way to propose the actions, and other subjective aspects…This phase is not finished yet since the system is going to be submitted to the final user on January, 2001. A protocol and training procedures for the effective use of the Supervisory System would be necessary. Syndromes such as "the analysts are scared that the computer would replace them", or disuse or misuse of the system should be avoided. Experts have to find easy to use the system and see that the Supervisory System will not replace but support them to solve or simplify their everyday tasks.

8.5 Field Validation of the Entire System and Evaluation of Usefulness

The main objective of field validation was to test the use of the overall Supervisory System *in situ*. We were attempting to test the system within its real environment and to identify needs for further modifications. The system performance was tested in its actual operating environment working as a real-time decision support system for more than 5 months (and still is going on). During that validation period, the Supervisory System dealt with several real type-problems. This phase of evaluation was conducted using a quite advanced prototype and enabled to make refinements and improvements to the Supervisory System, still uncovering unexpected errors or revealing cases not handled by the system. The problem in using a poor evolved prototype in the field test is that the system may lose credibility before the users get a chance to see the final product. To avoid this, we have to clarify that a prototype may not be as complete or as intelligent as they might expect.

During this 5-months period of exhaustive validation of the Supervisory System (from September 1999 to February 2000), it has been able to successfully identify 123 different problem situations, suggesting suitable action strategies. In the Table 27 we can see some of the results of the entire system validation. From those, 55.3% of the situations were identified the same day, 24.4% with 24 hours or more in advance, 12.2 were undetected and only 8.1% were incorrectly detected. Most of the situations detected 24 h in advance were identified as *transition state or tendency of the process to a specific problem*. Among the situations detected, 17 correspond to foaming, 2 to rising, 9 to filamentous bulking, 16 to underloading, 8 to deflocculation (including possible inhibitors), 10 to hydraulic shocks, 15 to mechanical faults, 5 to primary sedimentation deficient, 2 problems on clarifier of non-biological origin (sudden oscillations of upflow velocity and bad performance of clarifier due to too high biomass concentration) and 7 to influent nitrogen shock. It is noteworthy that many of these situations last more than only one day but they are counted as different situations every time the Supervisory System detects them.

Supervisory System Performance			
	≥24 h in advance	same day	Percentage (%)
Situations correctly detected (+)	30	68	24.4 55.3
Situations incorrectly detected (-)	10		8.1
Situations undetected	15		12.2
Filamentous bulking	5	4	7.3
Non-filamentous bulking	-	-	0
Foaming	7	10	13.8
Rising	-	2	1.6
Underloading	8	8	13.0
Organic Overloading	3	1	3.3
Organic shock	-	3	2.4
High influent Total Nitrogen concentration	-	7	5.7
Hydraulic Overloading	3	7	8.1
Deflocculation problems (incl. toxic shock)	4	4	6.5
Primary treatment problems	-	5	4.2
Mechanical or electrical problems	-	15	12.2
Problems on clarifier (non-biological origin)	-	2	1.6

Table 27 Overview of the field tests results

For each real case study solved (or not) during the field test validation, any validation technique for CBS and ES can be applied to the corresponding module. Moreover, feedback from experts and users was elicited via observations and comments on the system in use, frequent meetings and application of questionnaires. In this sense, besides the questions presented in the ES validation, the following additional questions were included in the field test questionnaire:

i. do you believe that the Supervisory System facilitates the decision process ?
ii. how do you think is possible to improve the system ?
iii. list advantages and disadvantages of using the system.
iv. evaluate the overall performance of the system as very good, good, fair or poor.

The application of these questions and the field validation itself in relation to the real world without any control also enables the evaluation of the usefulness of the developed system. Usefulness evaluation includes several criteria: productivity, the reliability of the system's response, the size of the knowledge base, the time required to solve a typical problem (response time), the difficulty of problems that can be solved, availability, capability,…All these criteria relates to the efficiency, effectiveness and capability of the system developed. The judgements for evaluating usefulness consists in assess each criterion, combine them and compare for both situations: with and without the Supervisory System. Features related to the usefulness of the system are implicitly commented in some of the case studies next presented.

This evaluation phase enables again to identify errors of faults in any kind of concepts (objects, attributes, values, problem-solving and control strategies…) of each module of the Supervisory System implementation. They can be deleted, changed or added.

The experience obtained in the application and evaluation of the performance of the overall system into a real WWTP, as well as the experts' opinion (both from WWTP responsible and owners) will be very useful to re-design certain parts or tools of the prototype in order to build the definitive application for the final user (the plant manager of the operating company), which should be a tool still more useful for supporting the WWTP management and control. In our case, a validated run-time of the Supervisory System will be submitted to the plant manager on January 2001.

8.5.1 Examples of Real Case Studies to Evaluate the Field Performance of the Supervisory System

This section presents five real cases studies corresponding to different real operational process states. These situations took place in the Granollers WWTP during the five first months of the field validation of the Supervisory System. These situations are relatively frequent in wastewater treatment plants and are some of the especially troublesome to solve with classical numeric control systems.

Thus, a classical control system cannot easily identify problematic situations requiring quantitative and qualitative information (*e.g.*, *in situ* plant observations or microscopic examinations) and thus, it would prevent a correct action. On the contrary, the Supervisory System conveys a systematic examination of the whole information. This system establishes and interprets relationships among the different variables much easier than plant operators in manual control (data from sensors, lab results, microscopic observations, trends of variables...). Therefore, the Supervisory System is able to detect and to diagnose rapidly any of these kinds of problems (*e.g.*, with microbiological origin as filamentous bulking, foaming,…). The temporal evolution of the values of some variables enables to detect some problems before severe episodes occur in the plant. This fact is very interesting to prevent a total modification of the microorganism population of the activated sludge process in problems of biological origin. Otherwise, for example whenever a severe problem of filamentous bacteria proliferation is presented, long periods of time may be necessary to recover the biological culture or to re-direct the process to its normal state.

Besides, the use of simulators adds another advantage to the Supervisory System, because although the expert could have an idea of how the system is going to evolve, he/she cannot foresee the exact change of certain variables, which can be obtained with the model of the process.

Each case study is presented following the same methodology: first, the involved period with the supervised days are indicated. Secondly, a summary of the problematic episode is given by means of a table that summarises the most relevant variables and the situations diagnosed for each day. Next, each one of the days supervised is explained with more detail, focusing on the new rules fired and the cases retrieved. Finally, some comments to the diagnosis and actions carried out are given. In the first case study, the most relevant features of each phase of the supervisory cycle (data gathering and update, diagnosis, supervision, prediction, user-validation and action phase and, evaluation phase) are extensively depicted. The other days presented are described with less detail, putting special emphasis in the new situations detected.

8.5.1.1 Case Study #1

Period: from September 26th to October 3rd, 1999.

Description of the situation: This situation corresponds to an excessive growth of *Microthrix Parvicella* due to the repeated situation of too low F/M ratio during several consecutive days. This unbalanced F/M gives favourable conditions for the growth of different species of filamentous bacteria. The excessive proliferation of *Nocardia* sp. or *M. Parvicella* induces the consequent development of biological foams (Foaming), which can accumulate biomass solids and reduce MLSS concentrations. The detected problems and both the quantitative and qualitative values of the most relevant variables of this case study are summarised in Table 28.

Date	September 26th	September 28th	September 30th	October 3rd
Flow (m3/d)	low (18911)	normal (24554)	normal (24357)	normal (19934)
Influent-COD (mg/l)	low (487)	low (527)	Low (687)	Low (561)
MLSS (mg/l)	4730 (high)	high (4272)	normal (3750)	3991 (normal)
Presence Scum Aeration	few	some	common	abundant
Microthrix presence	-	few	common	abundant
Supervisory System diagnosis	Underloading	Underloading Transition to foaming	Underloading Foaming	Underloading Foaming

Table 28 Summary of the detected problems and qualitative values of the most relevant variables.

September 26th

Phase 1 of the Supervisory Cycle: Data gathering and update

As any other day, the Supervisory System gathers all kind of data stored in the evolutive database (on-line and analytical determinations from the different sampling points and qualitative data). The data gathered during

September 26th is presented in Table 29. However, this is not the only data used by the expert system since, when calculating the trend of certain variables in the reasoning process, it could need the values of previous days. In this case, the Supervisory System advices that the microbiological data has expired and it recommends a new observation.

	Influent	Primary effluent	Biologic effluent	Aeration and global
On-line data	Flow rate 18911 pH 8.2	Flow rate 18911 pH 8.0	Flow rate 18911 pH 7.2	DO1 0 DO2 1.9 Air flow ? Recycle 130 % Wasting rate 510 m^3 Vel. ascensional 0.56
Analytical data	COD 487 BOD 400* TSS 162 NH_4^+ 86.5* TKN 336 Total N 122 PO_4^{3-} 10.3* COND 5100 TERB 128	COD = 399 BOD = 319 TSS = 86 NH_4^+ 87.8 COND 5100 TERB 77	COD 66 BOD 24* TSS 12 NH_4^+ 66.1 TKN 87.2 NO_2^-/NO_3^- 0.4/0.4 Total N 88 PO_4^{3-} 6.5* COND 4900 TERB 11	MLSS 4730 MLVSS 73 V30 262 MLSS-R 4920 V30-R ?
Global data	-	% COD removal 18 % BOD removal 96.8* % TSS removal 46.9	% COD removal 83.5 % BOD removal 91.4* % TSS removal 86	SRT ? F:M ratio 0.16 SVI 55.5 Recylce/inflow rate 0.61 % COD removal 86.5 % BOD removal 94* % TSS removal 92.6
Qualitative observations	Brown Scums at aeration tank = few; White Scums at aeration tank = none; Sludge flocs at clarifier = none; V30-test observations = good settling; floc appearance = Large and well formed floc; sludge blanket level at the primary and secondary settlers and thickeners = normal Sludge floating at primary settler = none; Scums floating at primary settler = none			
Microscopic data	Filamentous bacteria presence = none*; Predominant filamentous bacteria = none*; *Zooglea* = none*; *Nocardia spp.* = none*; Type 021N = none*; *Thiotrix spp.* = none*; Type 0041 = none*; *Microthrix P.* = none*; Number of filamentous bacteria = 0*; Protos = common; *Aspidisca* = abundant*; *Euplotes* = none*; *vorticella* = common*; *Epistylis* = some*; *Opercularia* = none*; Predominant protozooa= aspidisca*; Biodiversity (number of dif. species) = 5*; flagellates > 20 µm = few*; flagellates < 20 µm = some*; *Amoebae* = none*; *Tecamoebae* = none*; *Rotiferi* = none*			

Table 29 The whole data available on September 26th. In red, the data used by the ES and, in blue, the data used by the CBS (*means expired)

Phase 2 of the supervisory cycle: Diagnosis

The Expert System scans the data collected from the plant and looks for *warning* or *abnormal* values (marked in red in Table 29, some are quantitative data, *e.g.* flow rate, COD…, and some are qualitative data, *e.g.* presence of sludge, V30-settling test observations…). These values evaluated by means of the meta-rules (intermediate alarm), will launch the corresponding rules to explore only some branches of the decision trees from the operational problems module, transition state module or fault detection module, which finally will infer the situation of the process. In this case, the evaluated meta-rules fire five collection (modules or sets) of rules extracted from the corresponding logic decision tree. Each decision tree corresponds to a possible problematic situation to analyse (the meta-rules used are not very restringing in order to check the maximum number of possible problems). First of all, the few presence of *brown* foams in the aeration tank surface launches the foaming_rules and does not invoke the rules of non-filamentous-foams category (or non-filamentous-foams_rules). The low value of influent COD invokes the organic-low-loading_rules. Moreover, the low SS removal efficiency launches the primary-settler_rules. Besides, the low value of SVI rejects filamentous-bulking_rules and invokes the non-biological-problems-of-clarifier_rules and the deflocculation_rules. Finally, the good settling signalled by SVI and V30-settling observations also rejects viscous bulking.

When exploring the foaming decision tree, the few presence of foams in the clarifier combined with the absence of foams in the V30-settling test and low SVI rejects the problem of foaming.

The following step was to detect a possible problem in primary settling (both mechanical or not). For this purpose, the inspection of primary wasting rate, abnormal colour or odour, primary effluent SS and turbidity, presence of sludge or foam floating on the primary settler surface, depth of sludge blanket level and analogical data from primary settlers (to know if there should be a mechanical problem with the settlers, bridge, pumps or other sludge or foam removing systems…) enables to decline any problem in primary settling that could be inferred by the system. Therefore, the system would recommend checking for possible clump pipes, manual valves closed, etc…or other faults undetectable with the data collected that could produce this problem.

Then, the Supervisory System explores for possible non-biological-clarifier-problems and deflocculation problems. The first one is refused immediately after checking that both effluent suspended solids and turbidity concentrations are not high and that there is no presence of sludge floc in the secondary settler surface. To infer a deflocculation situation, the expert system checks for the qualitative variables referring to the floc appearance and V30-settling test characteristics from the *macroscopic* observations of the activated sludge floc (already collected). These observations reveal that the activated sludge floc is well formed (disperse growth rejected) and high (not like pins) and that the sludge settling is fast and that a clarified supernatant is obtained (good settling; so pinpoint floc is also rejected).

Therefore, from all the trees explored, the only situation concluded was the detection of an underloading in the bioreactor. The diagnosis of underloading follows the paths based on the values of some numerical variables related to the global state of the process (low F:M ratio and low influent load, both fired) and on some qualitative information (referring to the presence of floating sludge on the clarifier surface, in this case, not fired). As Figure 45 shows, the expert system activates an intermediate alarm, pointing the risk of underloading. In contrast, other possible conditions requiring quantitative or qualitative variables related to influent and effluent water quality (*e.g.* normal values of other analytical parameters like total suspended solids, effluent organic matter measured as chemical oxygen demand, V30-settling test observations and predominant protozoan) do not infer any diagnosis path.

Since this day does not present a high influent flow rate and influent COD is low, influent organic matter load is low. After checking the biomass concentration (it is not low), the diagnosis inference finally detects an influent under loading, causing low Food to Microorganism ratio (F/M). We can see the path followed to diagnose this problem marked in bold in the underloading decision tree shown in the Figure 45.

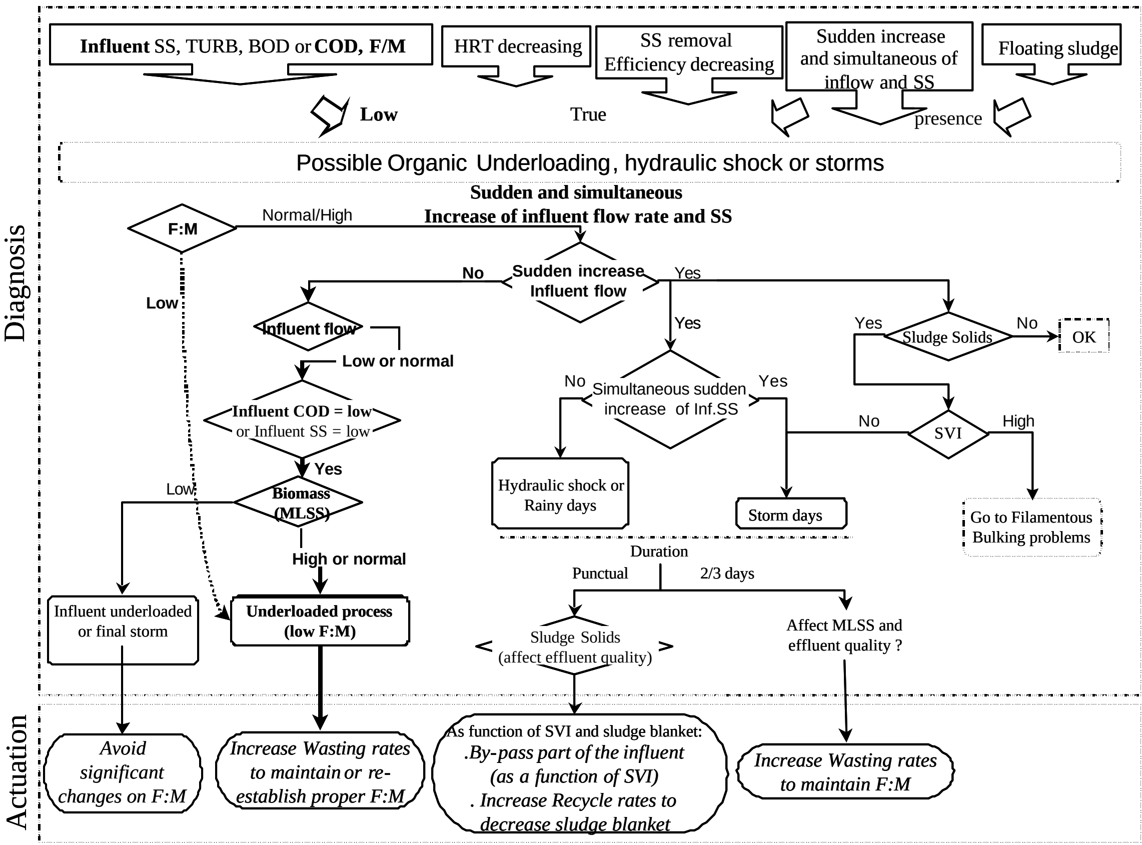

Figure 45 Picture of the underloading decision tree with the inference route followed in bold.

An the corresponding rule(s) extracted from this bold branch:

IF (

((the influent-flow rate-trend of tendency-granollers /= the symbol sudden-increase or the influent-flow rate of granollers /= the symbol great) and (the influent-COD of granollers = the symbol low) and (the biomass of granollers /= the symbol low))

or

(the Food-to-microorganism of granollers = the symbol low)

)

THEN conclude that the underloading of process_diagnosis-granollers = the symbol true

Once the expert system has concluded a situation, it will try to detect its specific cause. For this reason, the inference engine of the expert system launches the causes of underloading. In this example, both an underloaded influent (input BOD and flow rate have low values) and the high value of biomass concentration are the causes of the underloading experienced in the bioreactor (F/M ratio = 0.16 kg BOD/kg MLSS·d). With the situation and cause diagnosed, the expert system sends its conclusion to the third level of BIOMASS (supervision, prediction and action).

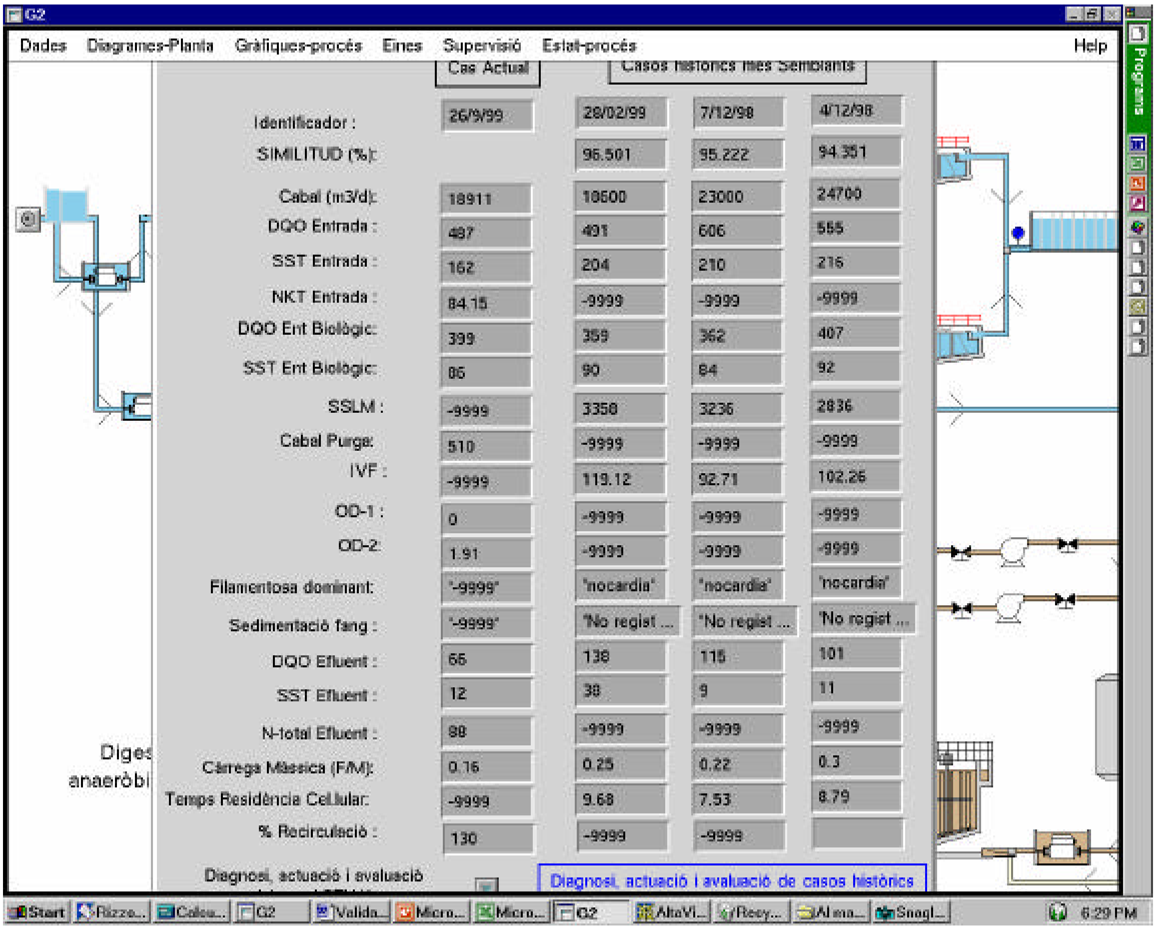

Figure 46 Current case (September 26th) and three more similar retrieved.

The Case Based System do not use the entire available information collected daily, but only the same 19-most relevant variables considered in the case definition (marked in blue in the Table 29). The first step of the CBS cycle consists of searching and retrieving the three more similar cases recorded in the case-library (initial case-library contained 74 real operating days). This comparison is based on a similarity criterion (*L'Eixample*, in our approach). As we have mentioned in the chapter explaining the CBS implementation, during the first months of field validation, we have used a library with plain memory because the retrieving time does not suppose a limiting factor (small initial case-library). Anyway, at any moment, we can compare the results of the hierarchical library with respect to the plain memory one.

In this example, the three cases retrieved from the case-library were the case#52, case#15 and case#14, sequentially. The actual case corresponding to September 26th and the three most similar cases retrieved are illustrated in Figure 46, in the way they are shown to the user in the CBS implementation. The best historic case included in the initial set of the case-library corresponds to the Case-02/28/99 with a similarity of 96.5%. Every case stored in the case-library does not only contain the case description, with the values of the 19-selected variables, but also the description of the situation, a proposal of recommendations on how to keep the process under control, and the effect of applying the proposed solution, that is, whether the result was a success or a failure. For example, the case#52 recovered in first place includes the following process description: This day corresponds to a day with a low loaded influent, a quite high biomass concentration and an abundant presence of *Nocardia* spp. causing *Foaming* of activated sludge.

By the time this example occurred, the cases stored in the case-library did not have any specific action strategy nor evaluation registered yet because those were the initial seed of the library coming from historical cases, which, before BIOMASS implementation, were registered without any action nor evaluation. This situation continued until the case-library was updated with recent supervised and completed days. Therefore, during the first months of the system evaluation, it only had information about the diagnosis of the case retrieved and general action strategies, but it was not able to suggest any specific action derived from the plant historic events. Consequently, the first case retrieved (Case-02/28/99) proposes the following general action in order to act in front of a foaming situation: "Physical removal of foams from bioreactor and settler, slight increasing (10% per day) of the wasting flow rate, and checking for trends of influent loading during the following 15 days. Check also for *Nocardia* population trends during a week.".

The cases retrieved in second and third place (case-12/7/98 and case 12/4/98, respectively) correspond also to episodes of Foaming caused by *Nocardia* spp., which grows and increases its concentration thanks to the low F/M ratio caused by the underloaded influent and quite high biomass concentration.

Phase 3 of the supervisory cycle: Supervision

The third layer of BIOMASS performs as the core of the system, as it receives and exchanges information and knowledge coming from the data level and the diagnosis level, forwards a resulting action that will be done through the actuators and establish interactions with users through the user-interface. So, the top component of BIOMASS includes a supervisory module that accomplishes the combination of the information and solutions provided by the ES and the CBS. This module is made up of a set of rules that must process the information received from the ES and the CBS, evaluating any possible conflict. Finally, this supervisor module suggests an action plan resulted of integrating the expert recommendations sent by the ES and the experiential action retrieved by the CBS (see Figure 47). Some of these supervision rules include criteria of similarity (if most similar case is really close to the actual, CBS solution should be *positively weighted*) or of unexpected situations (when facing to unforeseen situations not envisaged in the case-library, the ES will be favoured).

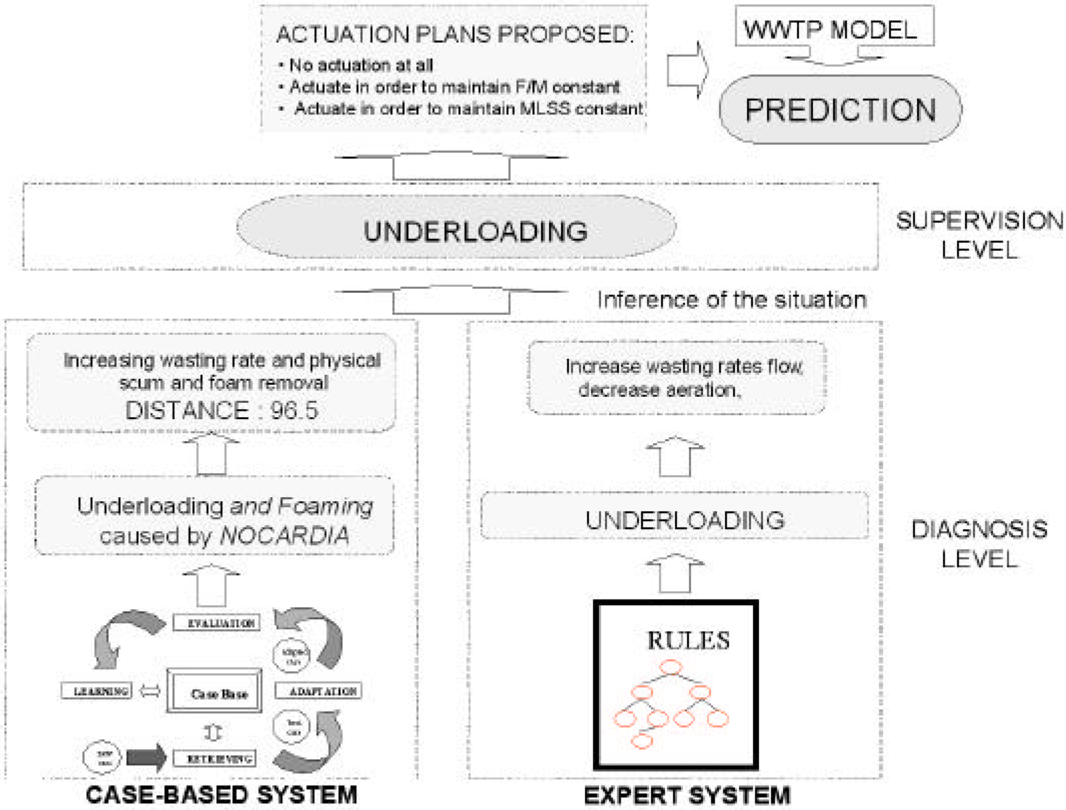

Figure 47 Supervision and prediction process

The supervision module for this day concluded that the plant was in an underloaded situation. This system also advises that this situation could evolve to a filamentous bacteria proliferation because the low F/M ratio is a typical cause of foaming and bulking.

The proposed action plan must always protect and preserve the floc-forming bacteria and microfauna population in the bioreactor and to re-drive the process to its normal operation. In this example, the solution proposes the following general action strategy:

- increase waste flow rate about 10% per day, until process approaches normal control parameters (F/M ratio and MLSS)
- the DO control loop has to remain active because the low organic matter input in the influent raises the DO sensor signal and the feedback controller will decrease sharply the airflow rate into the system. Excess DO will favour filamentous organisms growth
- check for trends of influent loading and biomass concentration during the following 15 days
- check for trends on *Nocardia* spp. and *Microthrix Parvicella* population every day
- if foaming persists or increases
  - consider the possibility of using the selector effect and the addition of chlorine into the recycle activated sludge stream

- remove scum and foams physically from aeration tank and clarifier to avoid surface trapping and foam recycle
- send a message to operators recommending how to remove physically foams and how to add chlorine (doses, location, and monitoring test with SVI)

A classical control system can detect a flow rate variation (*e.g.* a high influent flow rate in a storm situation or vice versa) and can actuate automatically on some of the floodgates that define the water flow (a by-pass, for instance). Moreover, it is possible to modify automatically the speed of the cleaning mechanisms in the grids or in the sand removal unit of the pre-treatment. However, a classical control system cannot detect, unless the plant has SS or BOD on-line sensors (almost none), whether the influent flow rate variation produces a diluting effect on the concentration of the pollutants (or vice versa, the inflow rate variation has brought an increment in solid or organic matter content). Depending on under- or overloading situation, the operation of the plant will be completely different. The proliferation of filamentous bacteria cannot either be noticed by a conventional control system based on numerical algorithms. Unlike a conventional control system, the Supervisory System enables a correct diagnosis, and avoids persistent underloading that could lead to filamentous proliferation by facing successfully this situation. Whereas the classical control only could act based on the value of the controlled variable, the Supervisory System may activate, deactivate or just modify the classical control strategy (*e.g.*, change the values of the set-points in order to adequate the control action to the specific situation) and proposes an additional action based on knowledge, or if it is necessary, can carry out additional reasoning processes to look for other operational problems and errors in mechanical devices or sensors. A well-calibrated mathematical model maybe could describe quite correctly the process in a situation of overloading (or underloading, not in a foaming situation), and therefore, an advanced control algorithm based on this model could manage the process in this situation but sometimes either the time for its resolution would be more long or classical control action would be insufficient to solve the problem than with a complementary knowledge-based action.

Phase 4 of the supervisory cycle: Prediction

Once the mechanistic model developed in GPS-X has been validated for the studied plant (in Granollers, validation phase is still going on), it can be used to support decision-maker when the integration between both proposals (from the ES and from the CBS) is not so clear. In these cases and, in other situations for which the mechanistic model has been successfully tested, the effects of the application of the solutions proposed can be evaluated. In this example, we simulate 30 operation days of the plant (five of them with an underloaded influent) and three possible control strategies to react to the underloading situation: (1) do not implement any action plan (instead, leaving the process recovering alone), (2) to act in order to maintain F/M constant and (3), to act in order to maintain MLSS constant (in fact, the two last suppose acting over the wasting rate). Of course, this model cannot simulate the apparition and growth of filamentous bacteria due to a repeated underloaded situation. As a example, Figure 48 shows the effects of applying the three action plans over the F/M ratio, MLSS and effluent TSS, COD and NH_4^+ of a simulated five-days underloaded influent.

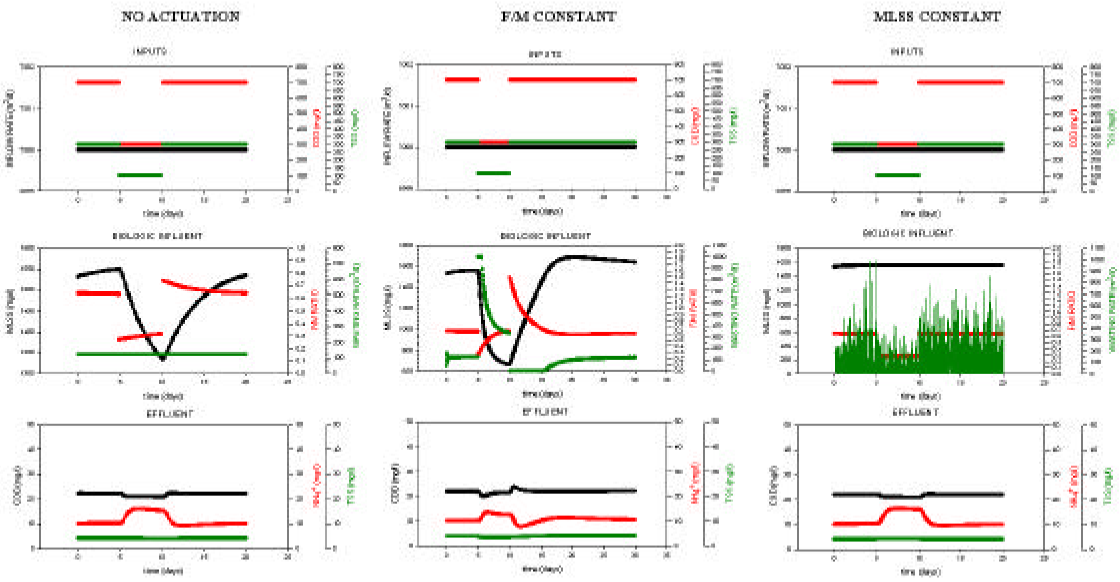

Figure 48 Effect of the application of different action plans over the plant evaluated with the mechanistic model

As it can be seen in the left figure, no action at all will cause a large depletion and long recovering in both biomass concentration (MLSS) and F/M ratio. As shown in the figure of the middle, the F/M control will cause a larger depletion on biomass concentration but the F/M ratio barely notices the effect (the recovery of normal value is very fast). Finally, the right figure indicates the large variation in F/M ratio with a MLSS control. Moreover, the last option supposes a continuous variation of the wasting flow rate, doing it more difficult to carry out to the real world than the F/M control option (where the wasting rate is fixed except in special circumstances, *e.g.* upsets recovering).

A black-box model based on soft-computing methods is being studied for any situation, special in those cases where mechanistic models fail (situations involving qualitative features, missing data…). Neither of them are still *really* implemented and integrated into BIOMASS. By the moment, they are accessed off-line.

Phase 5 of the supervisory cycle: user-validation and action

This prediction task carried out in the upper level supports the operators (or decision-makers) to take the final decision, which can be based upon the expert (ES), experiential (CBS) or numerical control. By the moment, the system always waits for the user validation of BIOMASS conclusions before implementing any kind of control.

Phase 6 of the supervisory cycle: evaluation

Finally, at the end of the day or next time the Supervisory System is activated, the plant manager makes an evaluation of the results of the action plan applied, which allow to close the CBS cycle, since this information complete the case information to be registered. This last step of the case-based system is essential to take advantage of its learning capabilities in order to avoid previous failure attempts or, on the contrary, to repeat successful actions to correct a problem.

In this example, the actual Case-26/9/99 will be registered with the description of the situation together with the action carried out (maintenance of the more relevant control parameters: wasting rate, recirculation and aeration. The wasting flow rate was not increased, although the Supervisory System recommended it. In this example, on September 28th we registered that "the action has not solved the problem two days after its application. On the contrary, the actions make the underloading situation even worse and the filamentous bacteria began to be detected" into the evaluation type-in box of Case-26/9/99. On September 27th, the wasting activated sludge rate was also insufficient to increase the loading rate.

September 28th

Detected situations: Following the inference process as explained in the first day, the Supervisory System warned again about an **underloading** of the biological reactor (low F/M ratio) whereas the plant was still removing the pollutants with normal efficiencies, like on September 26th. That day BIOMASS also advised of a possible **transition state to filamentous bacteria proliferation** due to the increasing presence of foams in the aeration tank and floc in the clarifier. After checking that the presence of filamentous bacteria was increasing and detecting a few presence of *M.Parvicella* in the activated sludge, the supervisory system inferred that the process was going towards a foaming situation (transition to foaming) favoured by a low F/M ratio. The plant began to show signs of foams of *Microthrix Parvicella* in the aeration basin.

Based on the cause of these problems (low F/M ratio), the Supervisory System recommended again an increase of the wasting rate in order to reduce MLSS and raise F/M ratio. Nevertheless, the real action carried out in the plant on September 28th consisted again of a low wasting sludge rate. During the same day, different tests with the aeration system made the DO level to reach very high values during low loaded periods. In these days, the airflow regulated was still based on manual valves. This problem was solved from November 9th 1999 because the DO control loop was implemented (based on a PI controller for each aeration compartment).

September 30th

Detected situations: The information gathered from September 30th made the intelligent Supervisory System to infer a F/M **underloading** for third time and a *Foaming* situation caused by a common presence of *Microthrix Parvicella*. The Supervisory System was also able to successfully determine the right causes of foaming. Poor greases removal and high F/M ratio were rejected as possible causes while high MLSS concentration and low F/M ratio were detected as true. Therefore, the system could recommend the corresponding specific action: an increasing of the wasting sludge rate to increase F/M ratio. During these days, the plant was partially nitrifying the high nitrogen loaded influent. This situation allowed the continued proliferation of *M.Parvicella* in the activated sludge process because it is one of the organisms that better grows in low loaded anoxic (denitrification) plants, since these organisms are able to use nitrate as electron acceptor in anoxic conditions.

Although an underloaded influent has been detected during several days, the wasting rate carried out in the plant was not enough to reduce significantly the biomass concentration (on September 26th, MLSS was 4730 mg/l and on September 30th, MLSS still was 3750 mg/l) and to restore an adequate food to microorganism ratio.

October 3rd

Detected situations: F/M **underloading** and **foaming** caused by *Microthrix Parvicella.* After, September 30th, the next days also presented an underloaded influent causing again a low substrate to biomass ratio, making worse the foaming process until reaching a severe episode, which affected the activated sludge settleability because SVI value has also increased until 218 ml/g (filamentous bulking effect caused by *M.Parvicella*). The sludge sedimentability was poor and there was an abundant presence of foams in the aeration reactor. The restoring of the F/M normal value involved an increasing of the waste activated sludge flow rate to decrease the biomass concentration and the sludge residence time, and physical foams removal from aeration tank and clarifier surface to avoid re-seed. The wasting rates from September 29th to October 3rd were a little higher than before the 29th but not enough to raise F/M ratio around 0.25 kg BOD/kg MLSS·d. Moreover, due to problems with the mechanisms of the sludge removing system of centrifuges, excess sludge could not removed from October 3rd to October 8th. The recycle activated sludge had to be increased to avoid solids overflow from the clarifier.

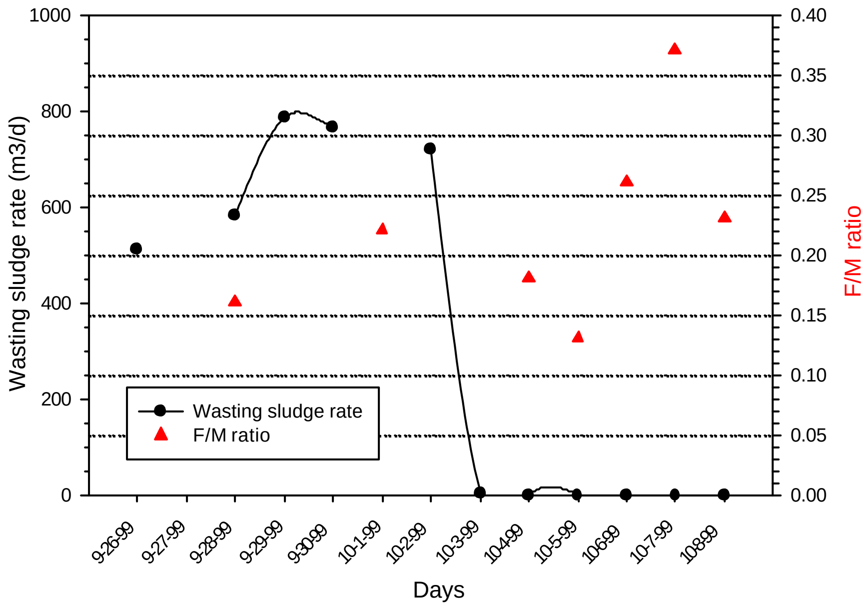

Figure 49 Real evolution of F/M ratio and WAS in the plant

Once the filamentous organism are well established and the foaming episode is severe, the corrective actions to solve the problem could be extended with any non-specific method (chlorination, chemical reagents addition or manipulation of the recycle activated sludge) or inducing the selector effect.

Figure 49 shows the evolution of F/M ratio and wasting rate in the plant during this case study. It can be seen how the F/M increases from September 28th to October 2nd with the increasing of WAS rate, as pointed by the Supervisory System. However a value over 0.25 could not be reached because the sludge wasting was stopped on October 3rd and was not re-started until September 9th. Therefore, during these days, the F/M ratio decreased again, except for the days October 7th and 8th, in which the F/M increase due to a high influent load.

Summarising, Table 30 shows the comparison of the situations diagnosed by the Supervisory System and the real situation lived by the plant during this supervised period (from September 26th to 3rd October, 1999). During three consecutive days (on September 26th, 27th and 28th, 1999), a low Food to Microorganism ratio (low F/M, a cause of filamentous organism proliferation leading to foaming) was advised by the Supervisory System whilst the WWTP was initially in normal operation and good removal efficiency. The process only started to notice the low F/M value on the third day of being detected by the Supervisory System, when it already detected the transition to foaming due to low F/M ratio.

Day	Situation detected by the Supervisory System	Real situation lived by the plant
9/26	Influent under loaded causing low Food to Microorganism (F/M) ratio	Correct operation
9/28	Influent under loaded causing low F/M ratio Transition to foaming due to low F/M ratio	Process underloaded (too low F/M values) Few presence of *M.Parvicella*
9/30	Influent under loaded Foaming caused by low F/M ratio	Underloading Increasing presence of foam in aeration/clarifier surface
10/3	Influent under loaded Foaming caused by low F/M ratio	Under loading Severe episode of Foaming of *Microthrix Parvicella* Solids overflow in peak flow periods

Table 30 Summary of the diagnosed situations versus real state of the process.

On September 28th the process presented the first signs of foams of *Microthrix Parvicella* due to F/M ratio while the Supervisory System was already pointing to a clear situation of Foaming caused by low F/M ratio. During the four next consecutive days, the process continued showing underloading and foaming. The process experienced even a worsening due to the continued underloading and, finally, it affected the suspended solids sedimentation and biomass concentration (SVI increasing). Both, the low F/M values and the foaming situation were detected by the Supervisory System at least within 24 hours in advance before appearing in the process, although it depends very much on the data frequency updating. Normally, this should give the plant manager enough time to take a control action to re-drive the process to the normal operation.

A classical control system cannot deal with certain problematic situations. For example, in this case study, first, it cannot easily detect a foaming situation because a numerical control algorithm cannot manage qualitative features. Second, once the problem is identified, a classical control system does not know how to solve it either. It is not able to suggest or carry out certain actions to complement or replace the automatic control actions to solve the problem (*i.e.*, the decision to increase the wasting flow rate due to low F/M and to remove foams from aeration tank requires certain degree of intelligent reasoning). Sometimes, if the classical control is maintained over the process, it can worsen the problem. For example, if the system maintains the same wasting flow rates, the underloading situation gets worse and thus, it would lengthen the favourable foaming conditions.

8.5.1.2 Case Study #2

Period: October 12th and 13th, 1999.

Situation: This case study refers to a couple of days with filamentous bulking and foaming caused by the microorganisms type 021N and *Microthrix Parvicella*, respectively. Moreover, October 12th presents a low loaded influent and undesirable denitrification in the secondary clarifier (rising). In addition, the Supervisory System launches several times per day a warning message that advices of clarifier problems due to sudden variations of upflow velocity during the peak flow periods.

Summary of detected situations and state of the plant:

Date	October 12th	October 13th
Flow (m3/d)	normal (23042)	normal (25525)
Influent-COD (mg/l)	low (527)	normal (851)
MLSS (mg/l)	Normal(3803)	normal (2147)
Primary N-NH_4^+ (mg/l)	normal (85.4)	high (101)
SVI (ml/g)	quite-high (194)	high (289)
SVI trend	4.5	105
Protozoan dominant	sessile ciliates	sessile ciliates/*epistylis*
Filamentous presence	abundant	abundant
Effluent N-NH_4^+ (mg/l)	low (55.3)	low (55.2)
Effluent N-(NO_2^-+NO_3^-)(mg/l)	high (2.3)	normal (< 1)
***Microthrix* presence**	very common-abundant	abundant
Type 021N	Few	common
***Nocardia* spp.**	None	none
Supervisory System diagnosis	Underloading, transition to bulking, foaming, and clarifier problems due to sudden variations of upflow velocity	Filamentous bulking, rising, foaming and clarifier problems (upflow velocity)
Undetected or bad-detected problems	Rising	-

Table 31 Summary of the detected problems and qualitative values of the most relevant variables

Detected problems on October 12th

The Supervisory System detects that the process is under loaded because it receives a diluted influent with respect to the biomass concentration. In this case, the system uses a previous value for the biomass concentration, it informs about it and recommends to the user to carry out a new analysis of MLSS concentration to update this value. This underloaded influent makes the foaming problem caused by the abundant presence of *M.Parvicella* worse.

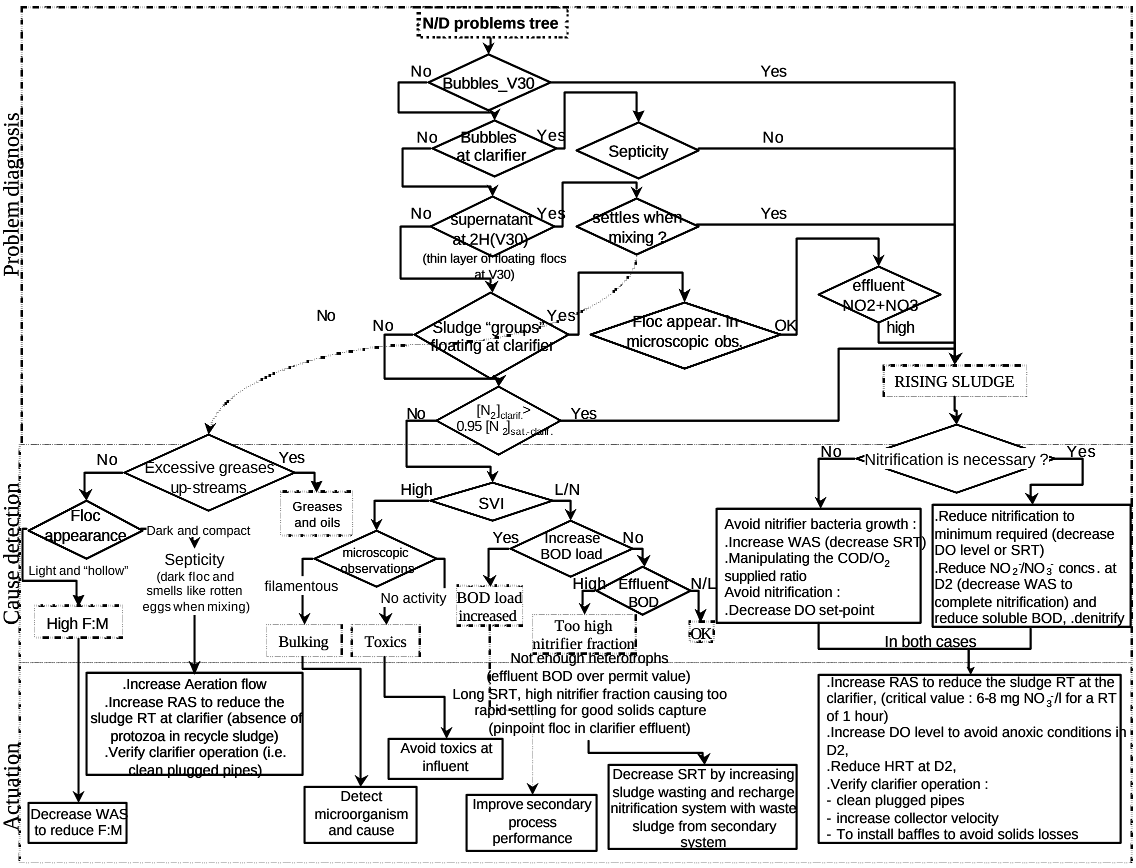

Figure 50 Denitrification in secondary settler (rising) decision tree.

Continuous oscillations of inflow rate causing sudden variations of upflow velocity in clarifier were also detected. One Archimedes screw of the Granollers WWTP impels 900 m^3/h and the inflow rate during the peak flows (3-4 hours during a day) is about 1000-1300 m^3/h, so if there are oscillations of the influent flow rate, these cause a continuing switching on and off of the second Archimedes screw. This fact provokes high and sudden oscillations of the upflow velocity in the secondary clarifier. These oscillations forces the secondary clarifier to work under continued changing conditions which difficult a good settling of activated sludge. The continuous variations of upflow velocity can provoke turbulences in the secondary settler and can lead to losses of previously settled sludge. These oscillations can cause solids overflow because of sludge with poor settling characteristics or with a high sludge blanket in the clarifier. This problem has been almost totally solved with the use of a primary settler as flow equaliser before entering the biological reactor.

The last problem detected by the Supervisory System is the trend of the process to attain a filamentous bulking problem (transition to filamentous bulking) since (1) there was a high presence of filamentous organisms, and (2) the SVI value was quite-high and the SVI-trend was not decreasing (on the contrary, it was increasing slightly), indicating bad settleability of the activated sludge. In order to calculate the trend of SVI, the values of the two previous days are required to the database (175 and 204 ml/g) and together with the actual value of SVI (194 ml/g), the SVI-trend is calculated.

A user-validation of the Supervisory System conclusions enables to discover undetected and incorrectly detected problems.

Undetected problems on October 12th

The WWTP also presents denitrification in secondary clarifier (rising) during this day. The undetection of this problem by the Supervisory System enabled to find the error in the rising diagnosis rules. According to the nitrification/denitrification decision tree, the rising problem was determined when (1) the effluent nitrate concentration was higher than 2 mg/l, (2) there was small floating sludge in the clarifier surface and (3), the activated sludge flocs were well formed. On October 12th, the premises (2) and (3) were accomplished but the first one was not because the effluent nitrate concentration was only 0.5 mg/l. Since the effluent nitrite was 1.8 mg/l, the sum of nitrite and nitrate (2.3 mg/l) was higher than 2 mg/l and susceptible to cause denitrification in secondary settler, whenever dissolved oxygen is absent and a carbonaceous source is available. So, this undetected problem involves the following modification in the premise of the rising diagnosis rule: to take into account the sum of effluent nitrite and nitrate (in this case, greater than 2 mg/l) instead of only the effluent nitrate (see Figure 50).

Detected problems on October 13th

A part from filamentous foaming, rising and problems in the secondary settling originated by sudden oscillations of upflow velocity (already detected on October, 12th), the knowledge-based decision Supervisory System also detects a filamentous bulking problem. It was identified thanks to the normal activity of microfauna, the high value of SVI value, the high presence of filamentous bacteria (common of type 021N) and the increasing value of SVI-trend.

Undetected problems on October 13th

None, all problems occurring at the plant were well diagnosed.

8.5.1.3 Case Study #3

Period: from October 17th to October 29th, 1999.

Situation: Underloaded process operating in conventional nitrification/denitrification mode. This case study corresponds to a period with recurring underloaded influent that causes a severe episode of Foaming and the growth of another filamentous bacteria (type 021N) causing sludge bulking. Besides, on October 29th, the system experienced deflocculation of the activated sludge floc.

Summary of detected situations and state of the plant:

Date	October 17th	October 25th	October 29th
Flow (m3/d)	normal (23726)	normal (23500)	normal (22298)
Influent-COD (mg/l)	low (664)	low (686)	Low (610)
MLSS (mg/l)	Normal (2960)	Normal (2502)	high (4098)

Effluent-COD (mg/l)	high (136)	normal (75)	Normal (97)
SVI (ml/g)	High (189)	High (291)	quite-high (134)
Protozoa dominant	sessile/crawling ciliates	sessile/crawling ciliates	Flagellates and crawling
Flagellates presence	Common	common	abundant
Filamentous presence	Excessive	excessive	excessive
Microthrix presence	Abundant	abundant	common
Type 021N	some	some	some
Supervisory System diagnosis	Underloading, foaming, transition to foaming, hydraulic shocks, high DO levels	Underloading, foaming, bulking and tendency to bulking	Underloading, foaming, bulking, deflocculation sludge
Undetected problems	filamentous bulking	-	-
Bad detected problems	-	-	tendency to bulking

Table 32 Summary of the detected problems and qualitative values of the most relevant variables.

Detected problems on October 17th

On October 17th the plant presents abundant filamentous foams in the aeration basin surface and low F/M ratio due to a high SRT value (8 days), underloaded influent and high MLSS concentration. The microscopic observation of activated sludge shows a population of microorganisms typical of an underloaded plant with predominance of the species *Epistylis* spp and *Aspidisca cicada* from the sessile and crawling ciliates groups and very low presence of flagellates. Organic biodegradation was achieved with very good efficiencies. However, this sludge presents poor separation sludge-water (high values of effluent SS and COD) due to a bad-formed floc since the activated sludge floc presents an open-structure (leading to low density) and great quantity of inter-floc bridges caused by the massive presence of filamentous bacteria. In these conditions, the Supervisory System easily detects underloading and foaming caused by an abundant presence of *Microthrix Parvicella*, which also has a high potential of bulking effect (SVI quite high). A side from those, the Supervisory System also detects a transition to foaming, that means that the actual tendency of the process is to continue being in the foaming state, indicating that the action carried out is not enough to solve this problem.

The Supervisory Systems also points out several times per day a warning of hydraulic shock in the secondary clarifier. These hydraulic shocks affecting the sludge settling are caused from abnormal high influent flow rates for a Sunday, due to strong raining and storms, which simultaneously caused an electric shutdown in the plant during eight hours. Finally, the process also experiences high values of DO level during the hours with lower flow rates.

Undetected problems on October 17th

Filamentous bulking caused by type 021N was not detected because of too much restringing premises in the bulking diagnosis rules. Initially, four conditions had to be satisfied to infer the filamentous bulking problem: activity of microfauna, high or quite-high values of SVI, high presence of filamentous bacteria and SVI-trends clearly indicating an SVI increasing (positive slope). The supervision of October 17th enabled to discover that a bulking is possible although the value of SVI-trend is decreasing (*e.g.*, a value of 189 ml/g, although lower than the previous ones, 207 and 288 ml/g, is still indicating filamentous bulking). Maybe the problem has begun to be solved but the SVI value is still high. On the other hand, in order to detect tendencies of the process to bulking situations, it seems reasonable to consider the SVI-trend.

The corrective action plan recommended by the Supervisory System involves an increasing of F/M ratio until normal values and decrease SRT (and MLSS) by means of increasing wasting rates. In the user-validation phase, the expert would upgrade the action plan with (1) a better control of airflow supplied (DO control) and (2) upgrading of in-plant processes to avoid high loaded side-streams (since it seems to be the cause of type 021N growth).

Detected problems on October 25th

On October 25th, the system detected underloading, foaming, filamentous bulking and tendency to continue suffering activated sludge bulking. As checked in the microscopic observations, the excessive presence of filamentous bacteria avoid correct floc formation and interferes seriously with the sludge settling and compactation since produce a great open-structure and bridging between flocs. The bioreactor and clarifier surface contain large quantities of filamentous foams. The Supervisory System identified neither undetected nor bad detected situations on October 25th. The Supervisory System recommendations were to take drastic measures to increase the F/M ratio and reduce SRT by increasing the wasting rate and avoid foam trapping in the aeration basin.

A testing phase of primary sludge pre-digesting was initiated on October 25th in order to produce easily biodegradable organics (*i.e.*, volatile fatty acids-VFA-) to increase the denitrification capability of the plant.

Detected problems on October 29th

Underloading, foaming, filamentous bulking and deflocculation of activated sludge floc. The electric power cut occurred one week ago in the plant left the biological suspended culture in anoxic conditions during more than 8 hours, causing the death of part of the sessile and crawling ciliates and the abundant presence of the flagellates organisms. This condition together with the excessive presence of filamentous organisms led to the bad formation of the activated sludge floc (deflocculation). The Supervisory System recommendations were first to take care of the biological culture, that is reduce the wasting rates until sessile and crawling ciliates become dominant (check the population evolution with microscopic observation) and then, increase F/M ratio to diminish favourable conditions for foaming and bulking.

Bad detected problems on October 29th

Transition to bulking was incorrectly detected since the biological process was not really tending to bulking, on the contrary, it was leaving this problem. This mistake was caused by the incorrect diagnosis rules for detecting transition to bulking. Initially, this tendency was inferred when (1) the filamentous presence was ≥ common and the SVI was high or quite-high and the SVI-trend was not decreasing or (2) the V30-settling test observations indicated a bad settling sludge. Of course, this second condition indicates an actual bulking activated sludge but not necessary signifies a tendency to bulking.

8.5.1.4 Case Study #4

Period: from December 16th to 26th, 1999.

Situation: This case study corresponds to a period with an underloaded process and malformation of flocs (deflocculation) due to an unidentified cause (maybe a toxic shock), among other more typical problems. Several alarms of hydraulic overloading in the secondary clarifier are also launched during these days.

Summary of detected situations and state of the plant:

Date	December 16th	December 21st	December 26th
Flow (m3/d)	normal (20563)	normal (20105)	normal (20105)
Influent-COD (mg/l)	Low (637)	normal (777)	low (548)
MLSS (mg/l)	normal (2894)	normal (2637)	high (3043)
SVI (ml/g)	quite-high (177)	quite-high (172)	quite-high (168)
Influent TKN (mg/l)	Normal (61.4)	high (136)	high(155)
Flagellates presence	Low	low	low
Filamentous presence	abundant	Abundant	Abundant
Microthrix presence	common	common	Common
Type 021N	abundant	abundant	abundant*
Supervisory System diagnosis	underloading, foaming, bulking deflocculation, tendency to foaming, high influent TKN	bulking, deflocculation, foaming, tendency to foaming, high influent nitrogen concentrations	deflocculation,underloading, bulking, foaming, tendency to foaming, high influent nitrogen concentrations
Undetected problem	-	underloading	-

Table 33 Summary of the detected problems and qualitative values of the most relevant variables.

Detected problems on December 16th

Underloading, bulking, foaming, tendency to foaming, high influent TKN loading (high influent TKN concentrations and inflow rate not low) and deflocculation of the activated sludge floc. The diagnosis of deflocculation is possible after checking several facts: flagellates organisms presence is very low, *Vorticella Microstoma* is present in less than 1000 individuals and the supernatant of the V30-settling test is turbid although the total COD removal efficiency is low and the dissolved oxygen, biomass concentration and inflow rate are normal (or the settled sludge is compacted). The microscopic observations of activated sludge confirm this situation since a very little floc and a very low presence of flagellates are observed (also characteristic of underloaded process). This deflocculation of the activated sludge floc is probably caused by the inhibitory or toxic action of some substance entered by the influent, but this circumstance could not be confirmed. Moreover, the high presence of filamentous bacteria around the floc (both *Microthrix Parvicella* and type 021N) also affect adversely in the floc formation causing large quantity of inter-floc bridges and floc breaking. The Supervisory System recommends to increase the F/M ratio to avoid the cause of filaments growth and to eliminate the possible remainders of toxic.

Detected problems on December 21st

Filamentous bulking caused by type 021N, deflocculation, high influent TKN loading, foaming and transition to foaming. The most probably cause of the abundant presence of type 021N is the repeated low F/M ratio presented at the plant (nutrient deficiency and low values of dissolved oxygen are clearly discarded). These conditions favour the filamentous bacteria growth in front of the floc-forming bacteria, resulting in a very small and broken floc. Therefore, this floc presents a bad settleability and compactability in the secondary settler. Since the growth of type 021N organism was favoured by anoxic zones and VFA generated in the pre-digesting of primary sludge and there were not nitrates to denitrify (*i.e.* nitrification process stopped some days before probably due to some inhibitory substance in the influent), the anoxic zone was converted to aerobic to ensure the best possible conditions for the good formation of the activated sludge floc, and to try starting again nitrification.

The action plan carried out involved a high wasting sludge rate to palliate the underloaded situation and the reduction of recycle activated sludge to the minimum value to enable good sludge settling and compactation.

Undetected problems on December 21st

Underloading was not detected because of the lower limit for abstracting the influent COD (low values for values lower than 700 mg/l O_2). The use of crisp values in the definition of the qualitative modalities of the variables causes this problem.

Detected problems on December 26th

Underloading, filamentous bulking, high influent nitrogen loads, foaming, tendency to foaming and deflocculation activated sludge. In this case, another cause for the deflocculation problem was pointed : an excessive underloaded process due to a very old sludge. Old sludge causes a disperse growth of the activated sludge floc avoiding a good bioflocculation (SVI is not high, sludge floc is formed but it is very small and disperse, the plant effluent and V30-settling test present turbiditiy and there are not bubbles in the settling test).

Operational controls were still fixed to favour a good formation of activated sludge floc: high wasting rates (during the 24 hours) and minimum recycle rates (only one recycle pump) were maintained during several days. On December 29th, the activated sludge floc already presented better flocculation and compactation, the foams of *M. Parvicella* had highly decreased and there were no floating sludge in the clarifiers.

8.5.1.5 Case Study #5

Period: from January 17th to 23rd, 2000.

Situation: This case study corresponds to a period with an influent organic overloading due to landfill leachate. During this week, the plant has been receiving 20 batches (trucks) per day with very high content in organic compounds (high COD content) of leachate. The number of flagellates has experimented a huge growth (from 20000 to 200000) but ciliates organisms have not been significantly affected. Therefore, the effluent quality was not affected by this organic overloading.

Summary of detected situations and state of the plant:

Date	January 17th	January 19th	January 23rd
Flow (m3/d)	normal (20140)	normal (22788)	normal (17194)
Influent-COD (mg/l)	normal (946)	normal (873)	normal (801)
MLSS (mg/l)	high (5230)	normal (3672)	high (4740)
SVI (ml/g)	low (82)	low (94)	quite-high (161)
Influent TKN (mg/l)	108	normal (84)	normal (84)
Protozoa dominant	sessile/crawling ciliates	flagellates	Flagellates
Flagellates presence	common	abundant (> 100000)	excessive (> 400000)
Filamentous presence	common	Common	common
Microthrix presence	common	Common	Common
Type 021N	none	None	none
Supervisory System diagnosis	Organic shock, high influent nitrogen concentrations, foaming	Organic shock, high influent nitrogen concentrations, foaming	Organic shock, high influent nitrogen concentrations, foaming, transition to bulking

Table 34 Summary of the detected problems and qualitative values of the most relevant variables.

Detected problems on January 17th, 19th and 23rd

High nitrogen-loaded influent, foaming and organic overloading. The overloading situation can be detected (1) by a high influent COD, an inflow rate not low and a biomass concentration not high (organic overloading due to a high F/M ratio), (2), by a not low DO, a low COD removal efficiency, a not high influent flow rate and a sudden amplification of biomass concentration caused by the increase in organic material (organic shock, the consumption in the mixed liquor could be greatly enlarged) or (3) by both a sudden increase of biomass concentration and presence of flagellates and a normal DO and inflow rate, (organic shock) (see these paths in the organic overloading decision tree of Figure 51). The latter diagnosis route is the path followed in this example. The biological culture has suffered an organic shock but without toxicity since ciliates organisms are still present and alive. It should be an organic load with an easily biodegradable substrate since an optimal organic removal with a very clear effluent is attained. The large quantity and sudden increase of flagellates causes the apparition of carnivorous ciliates (*Litonotus* spp. and *Colpidium* spp.). The analysis of COD based on the integrated sample probably does not capture the effect of the landfill leachate since they are only unloaded during certain periods. The filamentous presence is moderate and does not interfere in the floc compactation (floc structure is not opened nor presence of bridging between flocs) but makes the foams persist in reactor/clarifier surface. On January 23rd, transition to filamentous bulking is also detected. Only small flocs (< 100 μm) could escape to the effluent in peak flows periods. The Supervisory System recommends to maintain stable the control and operational parameters (MLSS around 3000 mg/l and SRT of about 6-7 days, so wasting rates should be increased) and to check for *M.Parvicella*, SVI-trend and possible causes of the organic shock.

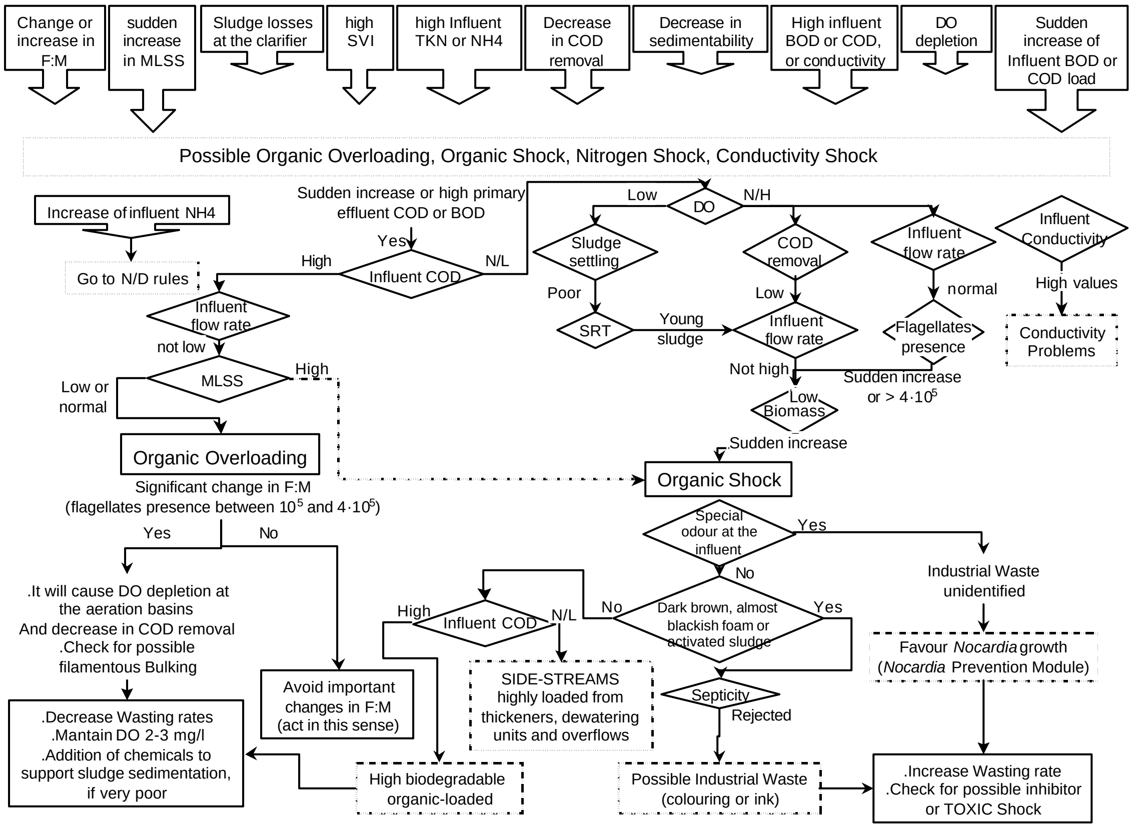

Figure 51 Overloading decision tree.

9 CONCLUSIONS

The major (or most relevant) conclusions arisen from this study are listed below:

1. The complexity of WWTPs requires the integration of different reasoning tools when looking for its optimal management.

2. There is a large and proved experience in the development of mathematical models and automatic control systems for WWTP. However, the use of knowledge-based systems in real plants is less kwon or more scarce.

3. Nevertheless, in recent years, a significant expansion in the field of knowledge-based systems has produced a relatively consistent base for their development.

4. Together, these facts have led us to the development, implementation and evaluation of a Supervisory System in a real plant (Granollers WWTP) integrating rule-based systems and case-based systems with classical control in the diagnosis module.

5. The use of rule-based systems in the WWTP domain is complex. The in-depth knowledge acquisition process is the bottleneck of the ES development. The acquisition of different sorts of knowledge (numeric on-line, numeric off-line, qualitative, experiential,…) is an essential step.

6. An exhaustive literature review and the establishment of a set of scheduled interviews with process experts was critical to build a group of decision trees that reflect the necessary knowledge to diagnose and solve most of the common WWTP problematic situations.

7. The use of automatic knowledge acquisition methods for the classification of the historical plant database (more than one year) allowed the adaptation of those decision trees to the specifications of the studied plant. The automatic knowledge acquisition methods also allowed to discover new situations which occurred during the study period and that were not previously provided either by the plant manager or by the literature review.

8. Despite their possibilities, rule-base systems, such as that developed in Granollers, present some difficulties when updating automatically their knowledge base by the final users (*e.g.*, add, delete, modify…rules or procedures). These difficulties make rule-base system not advisable as the only supervisory tool. Therefore, a case-based system was developed to complement the rule-based system in the supervisory tasks.

9. The CBS was easily implemented due to the availability of historical data from the same studied plant. These data enhanced the establishment of an initial seed for the CBS.

10. The good performance of CBS is very sensible to the variables selected to define the case and to their relevance (weight). These selection of variables and weight assignment should be carried out through iterative adjustments with the expert supervision.

11. Object-oriented programming and G2 provided efficient platforms for the implementation of supervisory systems, with real-time communication and on-line data acquisition.

12. The CBS for the Granollers WWTP was implemented considering 19 variables as the most relevant to define the case and either with plain or hierarchical memory. The initial case-based system contained a seed of 74 cases. After 6 month of continuous functioning, the CBS has enlarged up to 200 cases with action and evaluation, thanks to its learning abilities. On the other hand, the rule-based system implementation resulted in more than 700 rules and 200 procedures. The implementation of the overall prototype generates a G2-file with more than 500000 lines of code.

13. The Supervisory System validation should be considered as a multi-phase task: first, a partial validation of each reasoning module; and second, a final field validation of the overall integrated system.

14. Based on results from the validation process, the success of the Supervisory System is mostly influenced by the willingness of the plant owners to develop such systems.

15. During the operation of the Supervisory System for more than 5 months, in which the system was upgraded, the system was able to detect more than 100 different situations. An important number of those situations coincided with the current state of the plant, thus the Supervisory System acted like a notary of plant performance. In addition, the Supervisory System has been gaining capability to predict the situations that may occur in the plant (*i.e.*, transition states), showing a certain ability of prediction. This ability would hardly be obtained with other control techniques because the Supervisory System is the only one that uses simultaneously qualitative and experiential knowledge.

As a final conclusion of the whole work carried out, the Supervisory System developed and implemented in Granollers and presented in this thesis illustrates that these systems can be a useful tools to improve urban WWTP management.

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11 APPENDIX

11.1 CN2 Description

CN2 uses the covering approach to construct a set of rules for each possible class c_i in turn: when rules for class c_i are being construc ted, examples of this class are positive, and all other examples are negative. The covering approach works as follows: CN2 constructs a rule that correctly classifies some examples, removes the positive examples covered by the rule from the training set and repeats the process until no more examples remain. To construct a single rule that classifies examples into class c_i, CN2 starts with a rule with an empty antecedent (if part) and the selected class c_i as a consequent (then part). The antecedent of this rule is satisfied by all examples in the training set, and not only those of the selected class. CN2 then progressively refines the antecedent by adding conditions to it, until only examples of the class c_i satisfy the antecedent. To allow for handling imperfect data, CN2 may construct a set of rules, which is imprecise, *i.e.*, does not classify all examples in the training set correctly.

Consider a partially built rule. The conclusion part is already fixed and there are some (possibly none) conditions in the *if* part. The examples covered by this rule form the current training set. For discrete attributes, all conditions of the form $A_i = v_i$, where v_i is a possible value for A_i, are considered for inclusion in the condition part. For continuous attributes, all conditions of the form $A_i < (v_{ik} + v_{i(k+1)}) / 2$ and $A_i > (v_{ik} + v_{i(k+1)}) / 2$ are considered, where v_{ik} and $v_{i(k+1)}$ are two consecutive values of attribute A_i that actually appear in the current training set. For example, if the values 4.0, 1.0, and 2.0 for attribute A appear in the current training set, the conditions A < 1.5, A > 1.5, A < 3.0, and A > 3.0 will be considered.

Note that both the structure (set of attributes to be included) and the parameters (values of the attributes for discrete ones and boundaries for the continuous ones) of the rule are determined by CN2. Which condition will be included in the partially built rule depends on the number of examples of each class covered by the refined rule and the heuristic estimate of the quality of the rule. The heuristic estimates are mainly designed to estimate the performance of the rule on unseen examples in terms of classification accuracy. This is in accord with the task of achieving high classification accuracy on unseen cases. Suppose a rule covers p positive and n negative examples. Its accuracy can be estimated by the relative frequency of positive examples covered, computed as $p / (p + n)$. This heuristic was used in early rule induction algorithms. It prefers rules that cover examples of only one class. The problem with this metric is that it tends to select very specific rules supported by only a few examples. In the extreme case, a maximally specific rule will cover (be supported by) one example and hence have an unbeatable score using the metrics of apparent accuracy (scores 100% accuracy). Apparent accuracy on the training data, however, does not adequately reflect true predictive accuracy, *i.e.*, accuracy on new testing data. It has been shown that rules supported by few examples have very high error rates on new testing data.

The problem lies in the estimation of the probabilities involved, *i.e.*, the probability that a new example is correctly classified by a given rule. If we use relative frequency, the estimate is only good if the rule covers many examples. In practice, however, not enough examples are available to estimate these probabilities reliably at each step. Therefore, probability estimates that are more reliable when few examples are given should be used.

A more recent version of CN2 [Clark and Boswell, 1991] uses the Laplace estimate to estimate the accuracy of rules. This estimate is more reliable than relative frequency. If a rule covers p positive and n negative examples its accuracy is estimated as $(p + 1) / (p + n + N)$, where N is the number of possible classes.

CN2 can induce a set of if-then rules that is either ordered or unordered. In the first case, the rules are considered precisely in the order specified: given an example to classify, the class predicted by the first rule that covers the example is returned. In the second case, all rules are checked and all the rules that cover the example are taken into account. Conflicting decisions are resolved by taking into account the number of examples of each class (from the training set) covered by each rule. Suppose we have a two class problem and two rules with coverage [10,2] and [4,40] apply, *i.e.*, the first rule covers 10 examples of class c_1 and 2 examples of class c_2, while the second covers 4 examples of class c_1 and 40 examples of class c_2. The "summed" coverage would be [14,42] and the example is assigned class c_2..

CN2 handles examples that have missing values for some attributes in a relatively straightforward fashion. If an example has an unknown value of attribute A, it is not covered by rules that contain conditions that involve attribute A. Note that this example may be covered by rules that do not refer to attribute A in their condition part.

11.2 *k*-NN method Description

The nearest neighbour (NN) algorithm is one of the best-known classification algorithms and an enormous body of research exists on the subject [Dasarathy, 1990]. In essence, the NN algorithm treats attributes as dimensions of a Euclidean space and examples as points in this space. In the training phase, the classified examples are stored without any processing. When classifying a new example, the Euclidean distance between that example and all training examples is calculated and the class of the closest training example is assigned to the new example.

The more general *k*-NN method takes the *k* nearest training examples and determines the class of the new example by majority vote. In improved versions of *k*-NN, the votes of each of the *k* nearest neighbours are weighted by the respective proximity to the new example. In our experiments, *k* was set to 4.

Finally, the contribution of each attribute to the distance may be weighted, in order to avoid problems caused by irrelevant features. The feature weights are determined on the training set by using one of a number of alternative feature weighting methods. In our experiments, we used the *k*-NN algorithm implemented as described above:

Given two examples x = (x_1, ..., x_n) and y = (y_1, ..., y_n), their distance is calculated as

$$distance(x, y) = \sqrt{\sum_{i=1}^{n} w_i \times difference(x_i, y_i)^2}$$

where w_i is a non-negative weight value assigned to feature A_i and the difference between attribute values is defined as follows

$$difference(x_i, y_i) = \begin{cases} |x_i - y_i| & \text{if feature } A_i \text{ is continuous} \\ 0 & \text{if feature } A_i \text{ is discrete and } x_i = y_i \\ 1 & \text{otherwise} \end{cases}$$

When classifying a new instance *z*, *k*-NN selects the set *K* of *k*-nearest neighbours according to the distance defined above. The vote of each of the *k* nearest neighbours is weighted by its proximity (inverse distance) to the new example. The probability P(*z*,c_j,*K*) that instance *z* belongs to class c_j is estimated as

$$P(z, c_j, K) = \frac{\sum_{x \in K} x_{c_j} / distance(z, x)}{\sum_{x \in K} 1 / distance(z, x)}$$

where *x* is one of the *k* nearest neighbours of *z* and x_{cj} is 1 if *x* belongs to class c_j. The class c_j with largest value of P(*z*,c_j,*K*) is assigned to the unseen example *z*.

Before training (respectively before classification), the continuous features are normalised by subtracting the mean and dividing by the standard deviation so as to ensure that the values output by the difference function are in the range [0,1]. All features have then equal maximum and minimum potential effect on distance computations. However, this bias handicaps *k*-NN as it allows redundant, irrelevant, interacting or noisy features to have as much effect on distance computation as other features, thus causing *k*-NN to perform poorly. This observation has motivated the creation of many methods for computing feature weights.

The purpose of a feature weighting mechanism is to give low weight to features that provide no information for classification (*e.g.*, very noisy or irrelevant features), and to give high weight to features that provide reliable information. The mutual information *I(C,A)* between the class *C* and attribute *A* is thus a natural quantity with which the feature *A* is weighted in the *k*-NN implementation.

The mutual information between two variables is defined as the reduction in uncertainty concerning the value of one variable that is obtained when the value of the other variable is known. If an attribute provides no information about the class, the mutual information will be zero. The mutual information between the random variables *X* and *Y* is defined as *I(X,Y) = H(X) - H(X|Y)*, where *H(X)* is the entropy of the random variable *X* with probability mass function *P(x)*, defined as $H(X) = -\Sigma \log_2 P(x)$. For discrete *X* and *Y*, it can be also calculated as

$$I(X,Y) = \sum_{x,y} P(x,y) \times \log_2 \frac{P(x,y)}{P(x)P(y)}$$

For continuous variables, probability densities have to be used instead of probability masses and integrals instead of sums. The probabilities involved are in our case estimated from the training examples.

Unknown values in the examples are handled through a modification of the distance function between examples. Only features that have known values are used in calculating the distance, and the number of features for which both examples have known values is taken into account. The modified distance function is thus

$$d(x,y) = \frac{\sqrt{\sum_{i=1}^{n} w_i \times diff\,(x_i, y_i)^2}}{\sqrt{\text{number of features } i \text{ for which both } x_i \text{ and } y_i \text{ are known}}}$$

where $diff(x_i,y_i) = 0$ if either x_i or y_i are unknown and $diff(x_i,y_i) = difference(x_i,y_i)$ otherwise.

11.3 Autoclass Description

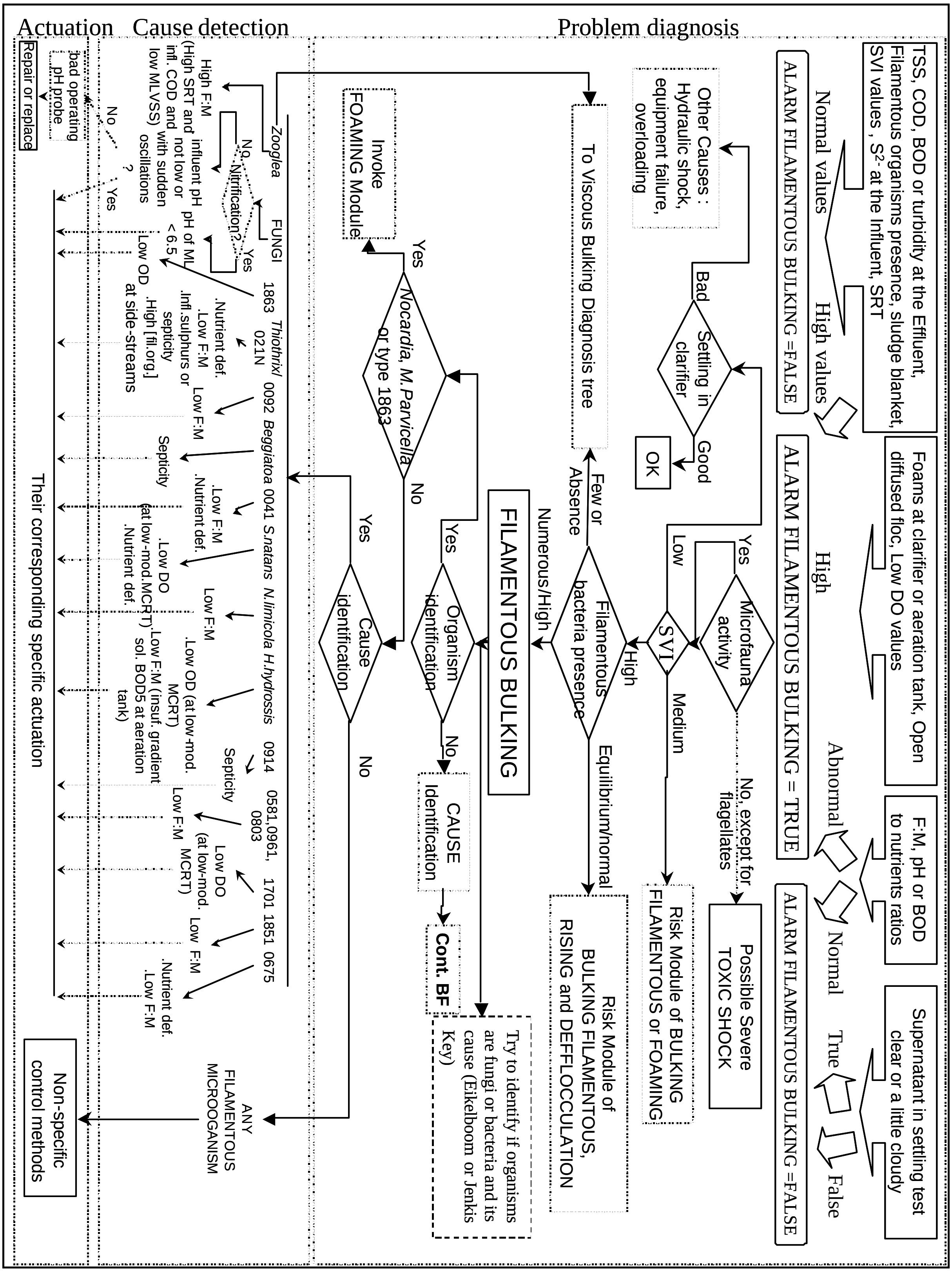
AutoClass is an unsupervised Bayesian classification program that seeks a maximum posterior probability classification. It has been developed by the Bayes group at Ames Research Center (NASA) to deal with the problem of automatic classification of data. AutoClass takes a database of cases described by a combination of real and discrete valued attributes, and automatically finds the natural classes in those data. It does not need to be told how many classes are present or what they look like; it extracts this information from the data themselves. The classes are described probabilistically, so that an object can have partial membership in different classes, and the class definitions can overlap. Although, theoretically, AutoClass should be autonomous in choosing the number of clusters, in practice we have to deal with several not very intuitive parameter settings, to optimise its behaviour.

11.4 Decision trees

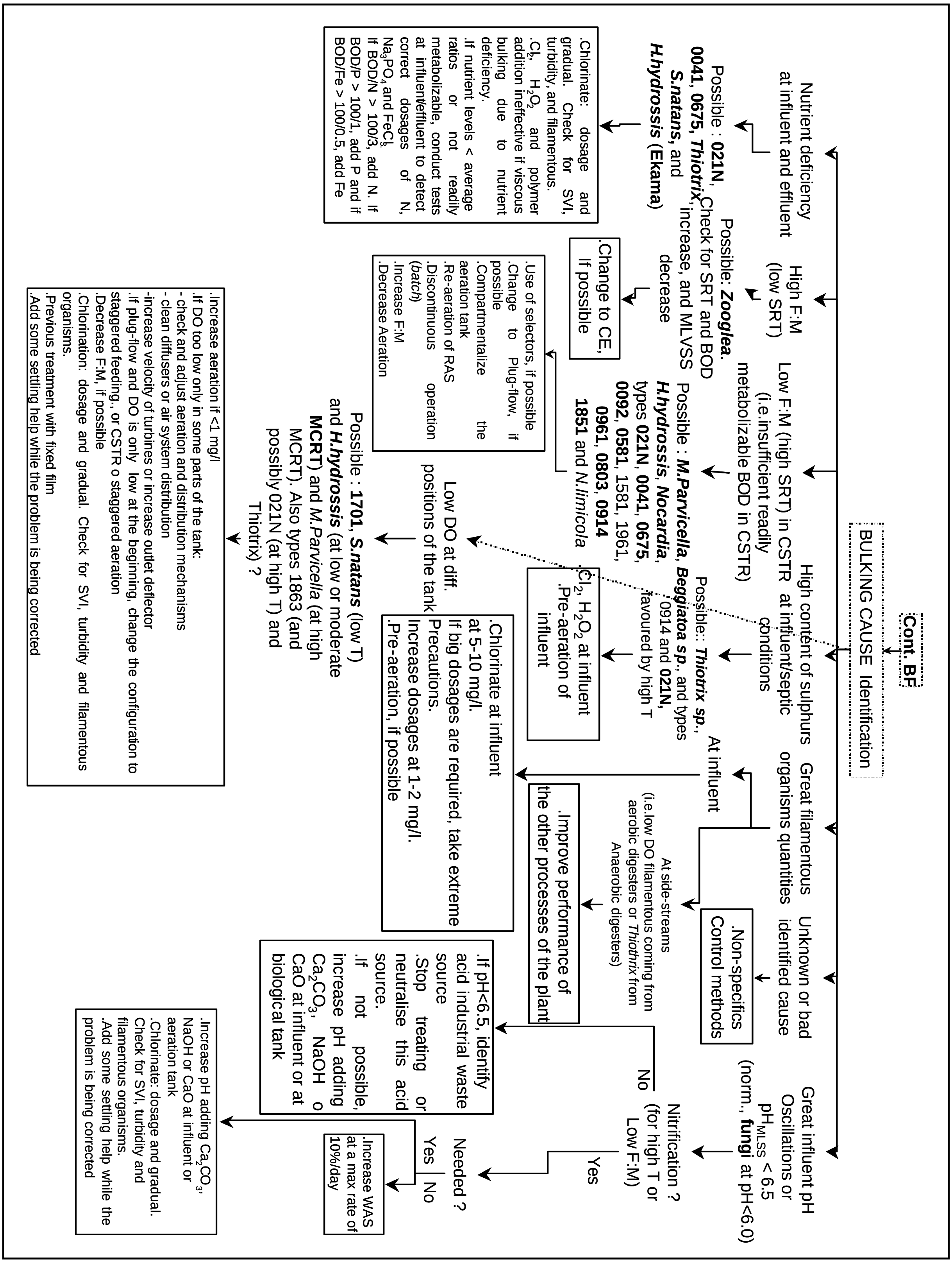
“The best way to escape from a problem is to solve it”.

-- Alan Saporta.

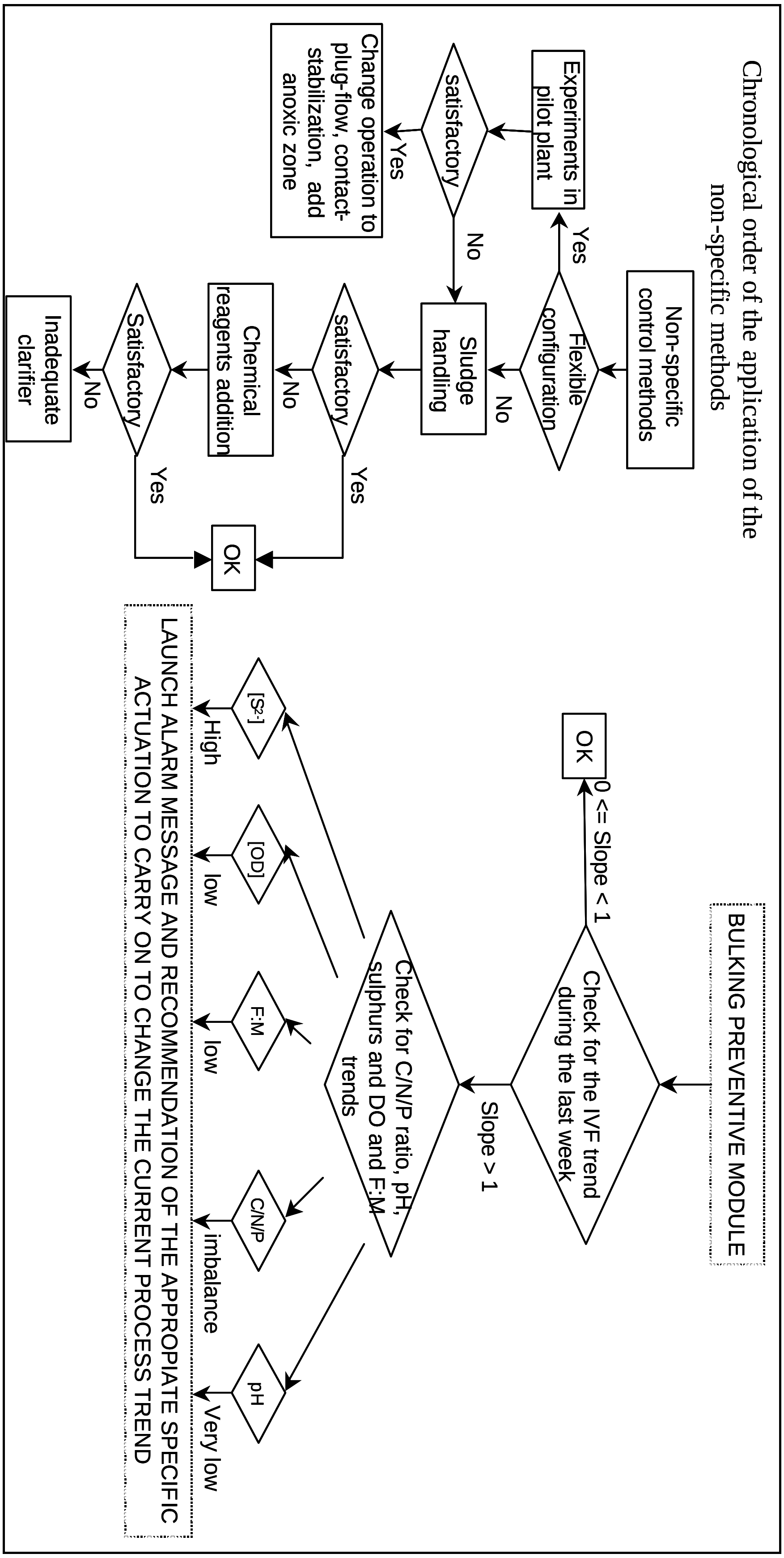
DECISION TREE FOR FILAMENTOUS BULKING DIAGNOSIS



DECISION TREE FOR FILAMENTOUS BULKING DIAGNOSIS (Cont.)



DECISION TREE FOR FILAMENTOUS BULKING DIAGNOSIS (Cont.)



Filamentous Bulking Definition

When the plant presents filamentous bulking, the activated sludge is bulky and settles slowly, caused by an excessive growth of filamentous bacteria which, due to its morphology, difficult the floc compactation. The filamentous bacteria interfere with the compactation and settling of the activated sludge floc either by forming open floc structures ("diffused floc") or by growing in profusion beyond the confines of the activated sludge foc into the bulk medium and bridging between flocs. The type of compactation and settling interference depends on the causative filamentous organism. This settling and compactation deficiency is detected by the sedimentability test of a 1 litre-activated sludge carried out easily at any laboratory. This test leads to a value corresponding to the sludge settled in 30 minutes (V30). Dividing this V30 per the Mixed Liquor Suspended Solids (MLSS), the Sludge Volume Index is calculated. The Sludge Volume Index (SVI) indicates the occupied volume in ml per 1-gram MLSS settled and, in bulking situation, should be greater than 150 ml/g. Also, in bulking situations, the microscopic observations of mixed liquor show the presence of filamentous organisms and the effluent quality is excellent, whenever extreme conditions are not reached or there is not solids washout. Inflow peaks can lead to floating sludge at the clarifier surface, if sludge blanket is high, provoking effluent sludge losses. This situation gives compactation problems of the settled material, in such a way that the supernatant is very clear since the inorganic particles and the dispersed bacteria are trapped into the net formed by filaments and flocs (there are a filtration of small particles that otherwise would escape from the clarifier). Nevertheless, sludge volume increases with time until it escapes to the effluent, if the causes are not counteracted. Sludge solids losses to the effluent could be due to two causes: treatment capacity exceeded (either hydraulic shock and/or organic overload) or deterioration of the sludge sedimentability due to the filamentous proliferation. That's why bulking is defined in terms of sludge sedimentability instead of terms of effluent quality of the clarifier. This poor sludge compactation also provokes a progressive decrease in the SS concentration of the RAS and, then, of the mixed liquor suspended solids.

Indicators/Symptoms

There are different conditions that could favour a possible bulking situation. Among the several signs of bulking conditions, we consider the increase of filamentous bacteria, the formation of a bulk floc, the decrease of DO, an abnormal pH, an slow settling velocity of the Mixed Liquor Suspended Solids and compacting poorly in the sedimentability tests (high SVI) but giving a quite clear supernatant or just a little cloudy, high values of COD, BOD or TSS at the effluent, a cloudy effluent, the presence of foams/scum/solids at the secondary settler or at the aeration tank, a high sludge blanket in the clarifiers and an small F/M ratio.

Diagnosis

The diagnosis process starts when the operator has introduced the results of his/her determinations into the system. In case microbiological information is available, then the activity of the microfauna would be the first parameter evaluated. An absence of the activity of the protozoan except for flagellates will indicate a possible severe toxic shock. If there is a normal bioactivity of the ciliates or the microbiological information has expired, then the bulking decision tree will evaluate the Sludge Volume Index (SVI).

As shown in the figure of Bulking decision tree, the SVI is the key parameter to infer the bulking situation. From this parameter, each path of the decision tree will be explained separately. If the value of SVI is low and there is a good sedimentation in the clarifier (that means low values of Suspended Solids at the effluent, < 25 mg/l), this tree concludes that the process is OK, that works under normal operation and stops the inference diagnosis. When the value of suspended solids is higher than 25 mg/l the system is able to conclude that the process is in abnormal state but rejects filamentous bulking as the cause. Other decision trees will be explored to detect the possible problems causing bad sedimentation (hydraulic shock, clarifier equipment failure, clarifier overloaded…).

When the SVI value is moderate (between 100 and 200 ml/g), the bulking decision tree leads the inference process to the state of "risk of bulking" and activates the risk Module pathways to evaluate the possible cause of this poor sedimentability of the sludge.

If the SVI is high, then the system checks for the relative abundance of the filamentous bacteria. Depending on this qualitative value, the inference tree follows different paths. In case of absence or poor presence of filamentous bacteria, the system concludes bad performance and investigates the logic tree of viscous bulking but rejects filamentous bulking. In the case that exists an equilibrium between filamentous and floc formers bacteria, then the bulking decision tree concludes that the state of the process is possible-bulking and activates the risk Module to check the possible causes. Besides, the system would evaluate the preventive modules of the denitrification in secondary settler (rising) and deflocculation situations. If the presence of filamentous bacteria in the activated sludge floc is greater than common according to the scale of Jenkins (abundant or excessive) [Jenkins, 1993], the filamentous bulking alarm is confirmed and the bulking situation is inferred. If the filamentous presence attribute does not exist in the system or it has expired, the system requires a microscopically examination to the operator but in order to be conservative, the decision tree would infer anyway the filamentous bulking situation.

Once the Bulking of the process has been concluded, the system starts the inference of the cause of the problem. For this purpose, it is really helpful to identify the predominant type of filamentous organism. Only 10-12 types of filamentous organisms account for the great majority of all bulking episodes. A key for filamentous organism identification in activated sludge based on [Jenkins *et al.*, 1993] is available on the expert system as a help module (with images and explanations) to facilitate the identification for unskilled operators. Main observations required to identify filaments are:

- Floc characteristics and filaments abundance
- Filament details (x1000)
- Filament characteristics: shape and location (at x 100) and associate growth, ramifications, diameter and length, cellular shape, size, intercellular granules (at x1000)
- Ink tests:

- presence or absence of capsule: crystal violet, India ink test.
- Gram+ (blue-violet), Gram- (red). Useful in identification of *M.Parvicella* and *Nocardia* spp.
- Intracellular granules: Neisser and PHB.

In case *Nocardia*, *Microthrix Parvicella* or type 1863 are detected as the predominant filamentous organism, the inference engine will invoke the foaming rules. When the filamentous organism identification is successful, the bulking decision tree evaluates the possible causes that provoke the proliferation of the predominant filamentous (see table 2). If the cause is well determined, then the expert system will propose a specific actuation method. Otherwise, if the cause identification is not successful, then a non-specific actuation method will be considered.

Cause Identification and Actuation

When coping with cause identification in the filamentous bulking situation, four different situations can arise:

(i) If the filamentous organism dominant and the cause are identified, the bulking decision tree proposes a specific solution. The specific actuations applied to the activated sludge conventional systems are biological or preventive control methods. That means that these methods treat the cause of the problem, trying to solve the problem forever. It means that these methods are not methods with an immediate effect. Against, sometimes, the definitive solution could take a long time (within a few days or weeks) but then, this filamentous proliferation due to the treated cause will never occur again. Table 1 summarises the different causes found provoking the excessive growth of a filamentous bacteria and the corresponding specific control action to solve the problem:

Possible Causes	Control action
Low F/M ratio	Low F/M action
Nutrient deficiency	Nutrient deficiency action
Septic wastewater/sulphide conc.	Septic conditions action
Filamentous org.conc. at the influent or side-streams	Filamentous concentration action
Low DO	Low DO action
Low pH or high pH variations	pH action
High F/M ratio (low SRT)	High F/M action

Table 1. Specific action associated to the cause determined

Among the different specific control actions for each possible cause we can distinguish between the actions related to the well identified causes and the actions related to the insufficiently identified causes (Low and high F/M). It has been verified that if there exist a gradient of soluble substrate in the reactor, then the activated sludge has a lower SVI value. When this gradient does not exist or when the substrate concentration is low, then the filamentous organisms are favoured with respect to the floc-formers (grow faster) because the former have a larger surface to adsorb the substrate (this is the basis of *selectors*). However, the selector effect cannot work if the substrate accumulation capacity (AC) of floc-formers bacteria is saturated (they do not have substrate accumulation and consumption capacity and then, their specific growth rate is lower and could be arrive to be about the growth rate of the filamentous organisms). For this reason, to get the total AC consumption of floc-formers organisms and promote their growth, the re-aeration of sludge recycle is a recommended practice. In the discontinuous or batch systems, there are almost no episodes of bulking because their configuration is like a plug-flow reactor, with high load at the early zone or period. Filamentous organisms are also favoured by wastewater rich in organic compounds of low molecular weight or by lipids of large chain. Mechanical stress, e.g. centrifugal pumps, can destroy microbial cellules and release lipids from membrane breaking than can make proliferate filamentous organisms. Both types of specific control actions (referred to well identified and poor identified causes) are explained in detail:

Actions related to the well-identified causes:

- Nutrient deficiency action: Nutrient addition. If DBO/N > 100/3, then try adding N, if DBO/P > 100/1, then try adding P and, if DBO/Fe > 100/0.5, then try adding Fe.

- Septic conditions action: Septic wastewater pre-chlorinating (before entering the biological reactor), pre-aeration of wastewater with high content of sulphurs to oxidise sulphide
- Low DO action: Increase oxygen flow rate at the biological reactor to ensure a dissolved oxygen level equal or greater than 1 mg/l at any moment.
- pH action: control influent pH or increase pH to values equal or greater than 7.
- Filamentous concentration action: pre-aeration or chlorinating of the influent.

Actions related to the insufficient identified causes:

- High F/M action:
- Low F/M action: .If possible, change the reactor configuration to plug-flow

.To operate in batch mode with intermittent feeding
.To compartmentalise the reactor to multi-reactors
.Re-aeration of recycle activated sludge (RAS)
.Use of selectors: there are different criteria of selector selection. Among them, most widely used are the kinetic selection criteria of [Casey *et al.*, 1995] and [Water SA, 1996].

(ii) When the predominant filamentous organism has been determined but not the cause, the bulking module proposes a non-specific actuation method. These non-specific methods or solutions try to soften the consequences of the excessive filamentous bacteria proliferation in activated sludge (the symptoms), and they have only a fast but temporary solution, since they don't solve the causes of this proliferation. These methods have three fundamental characteristics: fast application, reduced response time and attack of the problem not in a selective way but in a global fashion. They can be considered as short-term solutions or first phase of actuation, while the specific methods are being started or sometimes, as solution in very punctual appearance of bulking. The non-specific methods recommended are briefly mentioned at this point:

- If the plant has a c flexible configuration, and test in pilot plant are satisfactory, the change to plug-flow or contact-stabilisation configuration and addition of an anoxic zone.
- Recycle and waste activated sludge flow rates manipulation and modifications of the feeding point in the aeration tank: Increase recycle flow rate and decrease MLSS (by increasing waste flow). These are meth ods focused to prevent or to avoid possible losses of solids to the effluent due to the sludge blanket rising caused by the filamentous. Anyway, this biomass reduction in the system can reduce the removal efficiency and lead to a disperse growth of the activated sludge floc. The recycle sludge flow and feeding point modifications are actuations aimed at optimising the secondary settling performance.
- Addition of chemicals to the MLSS to improve the sludge sedimentability by increasing its specific weight. Simultaneously, these additional reagents can remove or not selectively the growth of the causal organisms: i.e., polyelectrolytes. Use of synthetic polymers (cationic polymers with high molecular weight or combined with anionic polymers) to improve cohesion of diffused flocs. It is important to conduct Jar-tests to know the optimal dosage and avoid counterproductive effects by overdosing. Polymers can be added at the aeration tank outflow or at the clarifier feeding point. They involve a higher cost with respect to chlorination but do not increase significantly the mass of solids. The addition of primary sludge or coagulants like cal or ferrous or ferric salts increase the specific weight of flocs, improving their settleability but result in n additional solid loading (increases the sludge production in 10-15%). The coagulant addition is not recommended for SVI lower than 200 ml/g. Doses are about 35 g Fe/m3 or 10-15 g Ca/m3 during, at least, 10 days.
- Addition of bactericidal products to selectively destroy the organisms responsible of bulking (specific attack to the filaments): Use of products with concentrations that works out lethal at the external floc (to kill filamentous microorganisms) but sub-lethal at the inside of the activated sludge floc. Use of chlorine, hydrogen peroxide (higher cost), or ozone. Chlorine is dosed in a well-mixed point, that is, directly in the aeration tank or in the recycle stream. Doses are about 5-20 kg Cl_2/TM SST up to achieving the target SVI. Initially, low doses are recommended and increasing little by little. In encapsulated microorganisms, chlorine does not destroy the capsule but only the organism. In this case, chlorine dosage should be stopped when the capsules look empty in the microscope, otherwise over-chlorination problems can arise. These problems result in effluent turbidity and sudden drop in SVI. In nitrification systems, dosage is lower and strict control of effluent nitrates and nitrifying capacity are required. If hydrogen peroxide is used as oxidant, doses should be higher and it is less selective (floc results more affected). This method is recommended for nitrification plants. Addition of 5-6 mg H_2O_2/l at the aeration tank up to a SVI value lower than 120 ml/g. Ozone dosage has a higher oxidant capacity, does not form by-products, does not inhibit (but promotes) nitrification but has major costs.

The last two methods do not cause any change on the conditions favouring bulking, so the filamentous bulking situation will return again when the application of these methods would stop.

If the filamentous organism identification is not possible because of the operator is not able to examine any sample of mixed liquor (e.g. unskilled operator or microscopic out of order), the system activates the general cause module to evaluate the possible cause of the hypothetic unbalanced growth of filamentous bacteria, inspecting among all the possible causes mentioned above for bulking. Again, two possible situations must be considered:

(iii) The causes provoking the bulking situation are determined among all the causes considered: low dissolved oxygen concentration, nutrient deficiency, abnormal pH or sudden pH fluctuations, low food-to-microorganism ratio, high influent sulphide concentration or septic influent and the nature of organic substrate.

Possible Causes	Type of filamentous
Low DO	Types 1863, 1701, *S. Natans (low T)*, *H. Hydrossis* (low or moderate SRT), *M. Parvicella* (high SRT) and possibly 021N (high T)
Low F/M ratio	*M. Parvicella*, *H. Hydrossis*, *Nocardia sp.*, Types 021N, 0041, 0675, 0092, 0581, 1581, 0961, 1961, 0803, 0914
Readily metabolisable substrate	*N. Limicola*, *Thiothrix*, Types 1851, 021N
Septic influent/sulphide concentration	*Thiothrix*, *Beggiatoa*, Type 021N, 0914 (favoured by high T)
Nutrient (N and P) deficiency	*Thiothrix*, *H. Hydrossis*, *S. Natans*, Types 021N, 0041, 0675
Low pH or high pH variations	Fungi
High F/M ratio (low SRT)	*Zooglea*
Filamentous organisms concentration at the influent or side-streams	*Thiothrix*, Type 021N

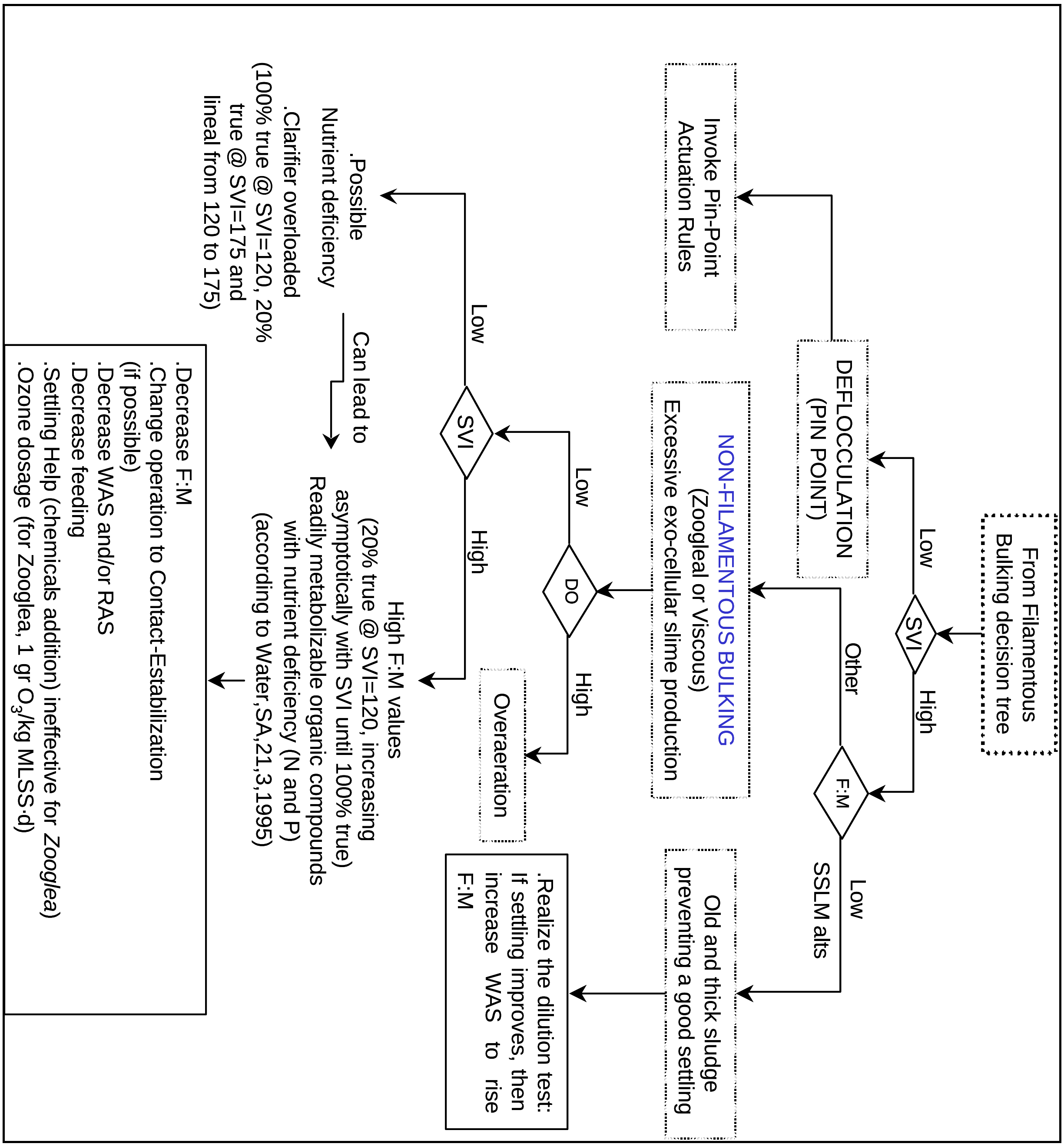
Table 2. Possible causes of filamentous bulking and their corresponding actions

The corresponding specific-actuation will be applied to the each detected cause:

- Low DO at different positions in the tank: increase aeration if <1 mg/l. If DO too low only in some parts of the tank: check and adjust aeration and distribution mechanisms. Clean diffusers or air system distribution, increase velocity of turbines or increase outlet deflector depth. If plug-flow and DO is only low at the beginning, change the configuration to staggered feeding, or CSTR o staggered aeration. Decrease F:M, if possible. Chlorination: dosage and gradual, checking for SVI, turbidity and filamentous organisms. Previous treatment with fixed film. Addition of some settling help while the problem is being corrected.
- Low F/M ratio (readily biodegradable substrate): High SRT in CSTR (i.e. insufficient gradient of soluble BOD in CSTR): Use of selectors, if possible. Change to Plug-flow, if possible. Compartmentalize the aeration tank. Re-aeration of RAS. Discontinuous operation (*batch*). Increase F:M. Decrease Aeration
- Septic influent/sulphide concentration: Cl_2, H_2O_2 at influent. Pre-aeration of influent.
- Nutrient (N and P) deficiency: Chlorinate: dosage and gradual, checking for SVI, turbidity, and filamentous. Cl_2, H_2O_2 and polymer addition ineffective if viscous bulking due to nutrient deficiency. If nutrient levels < average ratios or not readily biodegradable, conduct tests at influent/effluent to detect correct dosages of N, Na_3PO_4 and $FeCl_3$. If BOD/N > 100/3, add N. If BOD/P > 100/1, add P and if BOD/Fe > 100/0.5, add Fe.
- Low pH or high pH variations: If there is no nitrification, and pH<6.5, then identify acid industrial waste source. Stop treating or neutralise this acid source. If not possible, increase pH adding Ca_2CO_3, NaOH o CaO at influent or at biological tank. If nitrification is required, increase pH adding Ca_2CO_3, NaOH or CaO at influent or aeration tank. Chlorinate: dosage and gradual. Check for SVI, turbidity and filamentous organisms. Add some settling help while the problem is being corrected. If nitrification is not required, increase WAS at a max rate of 10% per day.High F/M ratio (low SRT): *Zooglea,* check for SRT and influent BOD increasing and MLSS decreasing. Change to CE, if possible.
- Filamentous organisms concentration at the influent or side-streams: chlorinate at the influent at 5-10 mg/l. If big dosages are required, take extreme Precautions. Increase dosages at 1-2 mg/l. Pre-aeration, if possible.

(iv) When neither the filamentous organism nor the cause are determined or few identified, the bulking module proposes a non-specific actuation method.

DECISION TREE FOR VISCOUS BULKING DIAGNOSIS



Viscous Bulking Definition

The non-filamentous bulking sludge is also called slime (jelly) viscous bulking due to its jelly-like consistency transferred to the activated sludge. This is a sludge bulking not associated to the excessive filamentous organisms proliferation but to the presence of microorganisms with large amounts of exo-cellular slime. This a phenomenon mainly related to the floc former microorganisms (*Zooglea Ramigera*), which could be detected with nigrosin or Indian ink and caused by the excessive exo-cellular polymer production. The jelly-like consistence of activated sludge causes a high water retention, which leads to the reduction of the compaction and settling rates of activated sludge. A viscous, not much compacted and hardly settled floc is formed. Also, there is a possibility of viscous foam formation at the clarifier surface.

Diagnosis

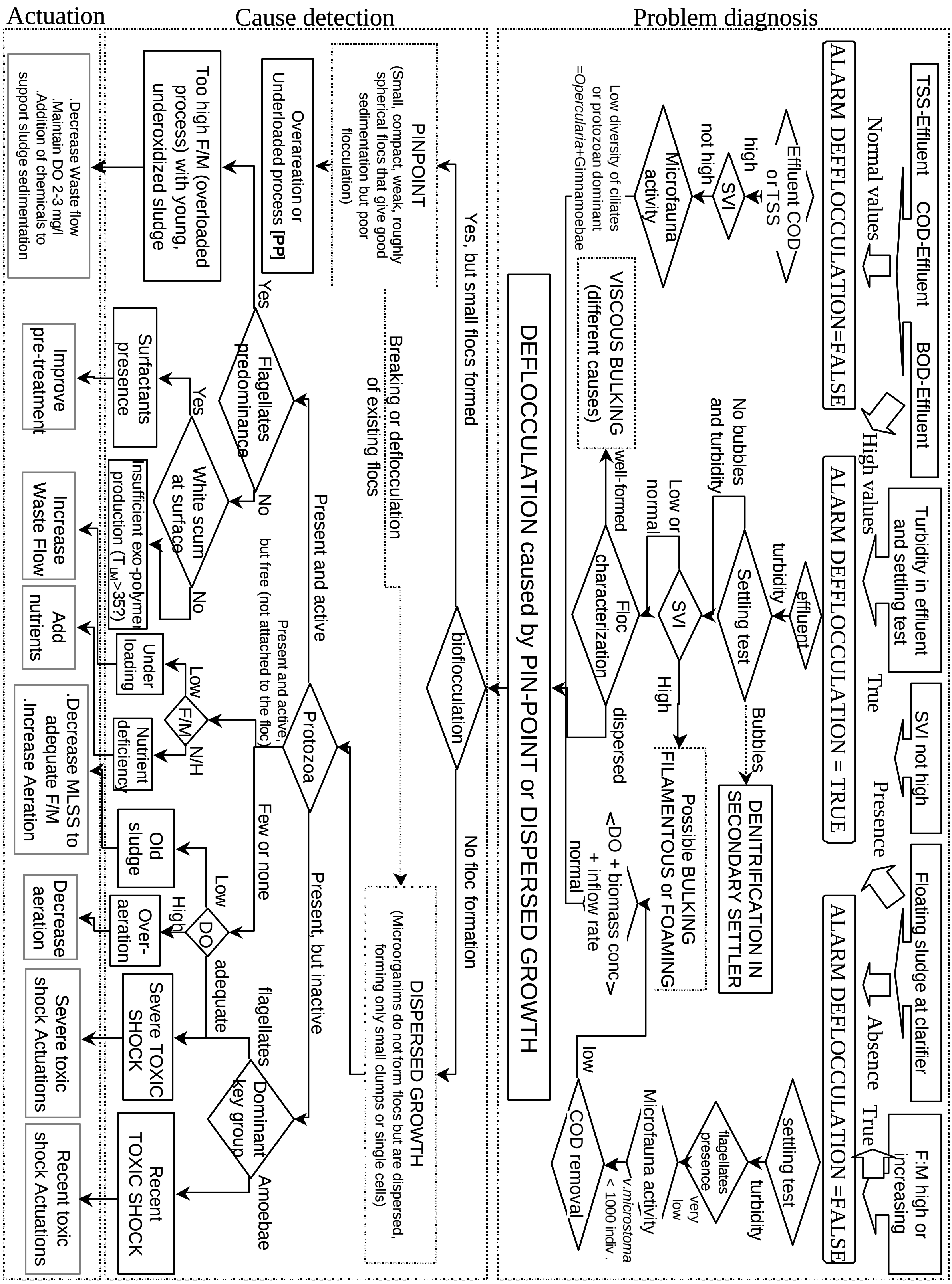
A low value of the sludge volume index determines whether a deflocculation situation (giving a pin-point floc) is presented or not. In affirmative case, the system will invoke a set of rules to identify the causes of this malfunction. Otherwise, the current Food to Microorganism ratio will be assessed. If the inference comes from the bulking decision tree, the first alternative will be by-passed since it has already been evaluated. Then, the assessment of the F:M ratio will allow distinguishing between viscous bulking and old sludge. If high values of mixed liquor suspended solids provoke a significant F:M decrease, then an old and thick activated sludge preventing a good settling performance will be diagnosed. When conducting the dilution test to the activated sludge, if settling improves significantly, then an increasing of Waste Activated Sludge (WAS) to rise F:M would avoid an over-oxidised sludge. With any other F:M value or when the presence of *Zooglea Ramiglera* in activated sludge floc became abundant or excessive, the non-filamentous or zoogleal bulking situation would be inferred.

Cause detection and actuation

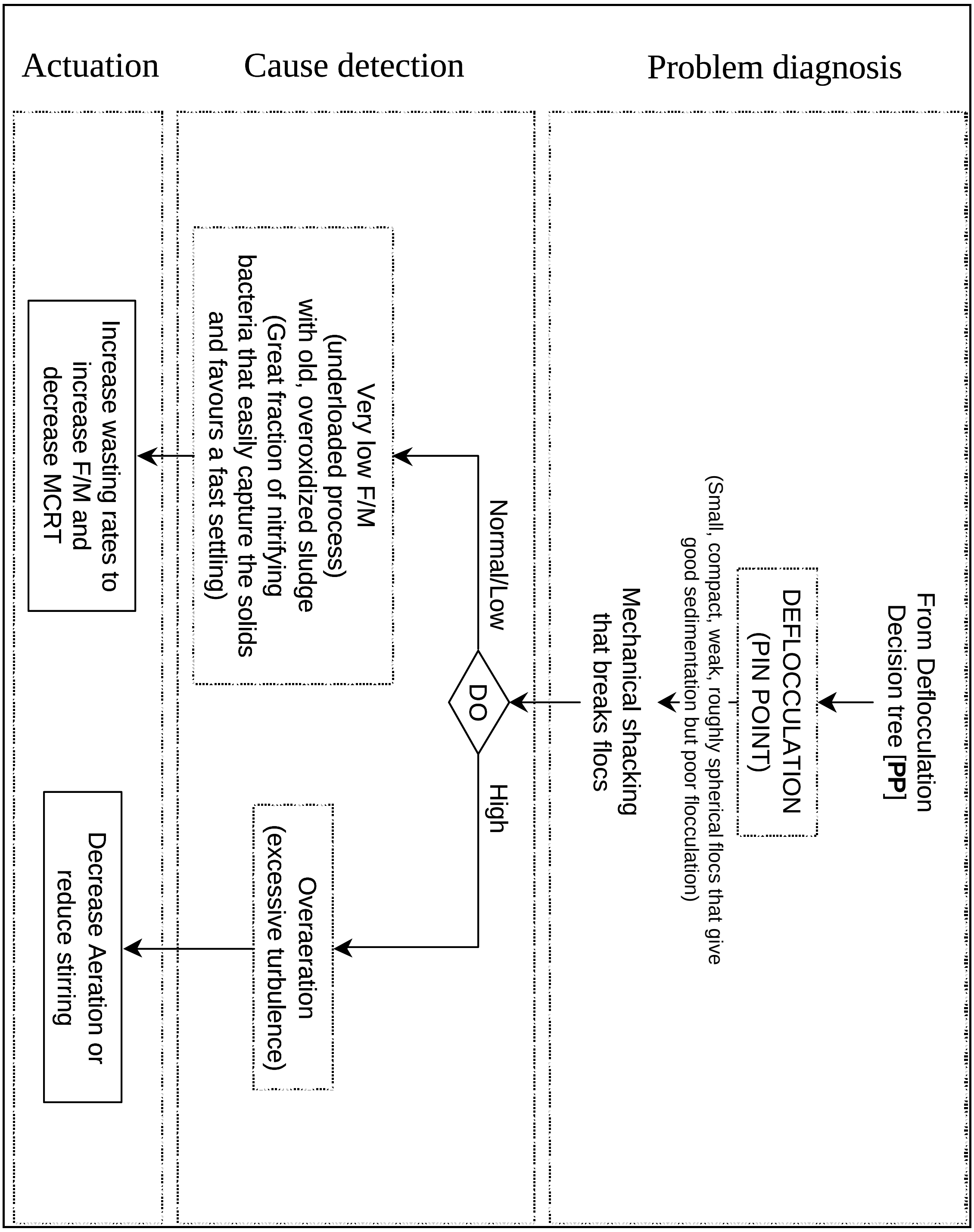
After the viscous bulking situation is well inferred, their causes will be studied. First, if the dissolved oxygen level during the 24 hours has experienced high values, the cause inferred will be an over-aeration of the activated sludge. A drop in the dissolved oxygen set-point would be suggested by reducing the aeration time or decreasing the airflow supplied. In contrast, if the latest 24 h-averaged dissolved oxygen level is not high, then sludge volume index is checked again. For SVI lower than 175, the nutrient deficiency is pointed as possible cause and can end in a high F:M episode. An overloaded clarifier is the reason that causes bad performance with 100 % of certainty at SVI equal to 120. The certainty lineally decreases up to the 20% of SVI equal to 175. For very high values of SVI, the high Food to Microorganism ratio is the most probably cause of viscous bulking. This is 20% true at SVI equal to 120 and increases asymptotically with SVI up to 100%. This biological reactor overloading is mainly caused by the repeated presence of readily metabolisable organic compounds with nutrient deficiency (N and P) according to [Casey *et al.*, 1995].

The *Zooglea Ramigera* is a very difficult filamentous organism to control : the chlorine, polymer or hydrogen peroxide addition to help settling result inefficient. An ozone dosage of 1 gr per kilogram of mixed liquor suspended solids and day seemed to give positive results. Anyway, if the high F:M ratio has been detected as the clear cause, the actuation efforts has to concentrate on decreasing this ratio. If the plant operation allows it, a good chance would be to change operation to contact-stabilisation. If not possible, the recovery of the viscous bulking problem hinges on solving the problem of too high mixed liquor suspended solids. A decrease in the WAS and/or in the RAS and/or in the plant feeding should be performed.

DECISION TREE FOR DEFLOCCULATION PROBLEMS



DECISION TREE FOR DEFLOCCULATION PROBLEMS (Cont.)



Deflocculation Problems definition
Deflocculation refers to a dysfunction of activated sludge separation process characterised by a turbid effluent but normal SVI (about 100 ml/g).

Indicators/Symptoms
There are different conditions that could favour a possible deflocculation situation. These set of signs includes higher values COD, BOD and TSS at the effluent than the normal, the observation of turbidity in the plant effluent and in the 30 minutes-settling test, the presence of floating sludge throughout the secondary clarifier surface, an SVI value not high and an increasing or high F:M value. All these signals launch an intermediate alarm of deflocculation, which will invoke the diagnosis rules for this operational problem.

Diagnosis
Key variables and checking order: effluent turbidity, qualitative features of V30-settling test, SVI and floc characteristics.

The diagnosis process starts when the operator has introduced the results of his/her determinations into the system. In case the qualitative information of the settling test is available, then the expert system will check for the turbidity and presence or not of bubbles. If bubbles are observed while doing the settling test, the inference path should be addressed to the denitrification in secondary settler (rising) decision tree. Instead, if there are not bubbles in the V30-measuring cylinder of sedimentation or this qualitative observation is not available for the system, the decision tree will guide the inference path to the checking for filamentous bacteria presence in the activated sludge. Only in case that the filamentous bacteria are numerous, the activated sludge could be suffering an episode of filamentous bulking or foaming (the decision tree for these problems identifications will be invoked). In other case of filamentous presence, the system will go on the deflocculation diagnosis. The next variable evaluated by the inference engine will be the floc characterisation. If it is well formed, the viscous bulking decision tree will be launched. On the other hand, if the flocs are dispersed, then the deflocculation situation is concluded.

A second branch to achieve the deflocculation diagnosis includes: flagellates organisms presence is very low, *Vorticella Microstoma* is present in less than 1000 individuals and the supernatant of the V30-settling test is turbid although the total COD removal efficiency is low and the dissolved oxygen, biomass concentration and inflow rate are normal (or the settled sludge is compacted).

Finally, a third way to diagnose deflocculation is specific to Granollers WWTP: high effluent COD or TSS, not high SVI and low diversity of ciliates or *Opercularia* and Gimnamoebae as predominant protozoan.

Two possible types of deflocculation are distinguished according to whether the bioflocculation is giver or not. If small flocs are formed, then the problem is named pin-point whilst if microorganisms do not form biological flocs but are dispersed, forming only small clumps or single cells, then the problem is referred as dispersed growth. These processes are distinguished in the cause detection module for deflocculation problem. When the free or disperse bacteria do not form consisting flocs, but growth in a disperse fashion, causing an uniform turbidity in the supernatant due to the small particles that do not settle (no zone settling of the activated sludge), then the activated sludge is living an episode of dispersed growth.

Cause detection and actuation for dispersed growth
When dispersed growth is diagnosed, the next variable to evaluate is the qualitative state of the protozoa of the activated sludge. Also, in this case, we need updated microbiological information (otherwise, the system will remember that it do not have current microbiological information). Any answer to this query concludes the dispersed growth situation. What is different is the cause leading to this problem.

If the protozoa are present in the activated sludge but they are quite inactive, then a poisoning of the biomass would be the cause. We can distinguish whether the toxic shock is severe or recent and weak according to the dominant key group of the protozoa [Madoni, 1994]. If they are the flagellates, a severe toxic shock load has occurred recently (possible industrial by-pass with metals, bactericide,...). The microscopic observations of the activated sludge show no activity and dead protozoan (the first affected are the sessile ciliates). Severe toxic shock load actuations involve to identify and to eliminate the source of toxic load. In very severe cases, a reseed with activated sludge from another plant or the addition of freeze-dried microorganisms is suggested. If an industrial source is identified, it is needed a pre-treatment in the own industry (enforce sewer-use ordinance).Otherwise, if the dominant key group are the amoebae, then there has been a recent toxic shock load (possible industrial by-pass). The first symptom is the cilia movement cease. Attached microorganisms remain inactive but swimming and crawling ciliates remain mainly active. The respiration rate of mixed liquor is lower than normal. The system indicates to check for the possible presence of toxics in the influent (metals, acids, caustic solutions or pesticides). A situation of nutrient deficiency for a long time can also cause this weak poisoning of the activated sludge. Recent toxic shock load actuations involve in first place to identify and eliminate the source of toxic load. If an industrial source is identified, it is also needed a pre-treatment in the own industry. If the toxics are still in the system, increase the waste flow rate to eliminate it with the excess sludge. Otherwise, if they are not in the system, decrease waste flow rate and to maintain the dissolved oxygen level superior to 1.5 mg/l. If the number of microorganisms affected were large, maybe it would be necessary to reseed with activated sludge from another plant or add freeze/dried microorganisms. If the nutrient deficiency is detected as the cause, then an addition of nutrient will solve the problem. In this problem, the addition of chlorine will be ineffective.

When the observation of activated sludge with a microscope shows an absence or a very few presence of protozoa (poor sludge in biodiversity and number of species), then the dissolved oxygen will be checked as the possible cause. If the DO level is the adequate, the system concludes again a severe toxic shock load and proposes the severe toxic shock load actuations. If the DO level is high, the cause inferred is an over-aeration. Over-aeration actuations involve checking for DO level and decreasing aeration if lowest DO reading in aeration basin is more than 4.0. Otherwise, if the DO level is low, then the system concludes that the process has a too old sludge (MCRT is too long). Old sludge actuations involve checking for the MCRT (normally, should not be longer than 9 days) and increasing sludge wasting to reduce MCRT and adapt the right F/M ratio. Eventually, aeration flow rate can be increased to overcome the temporary oxygen deficit.

When the observation of activated sludge in the microscope shows a normal presence of active protozoa but with predominance of free-swimming protozoan over the attached ciliates, then the F/M ratio decides which is the final cause. If the F/M is low, then the process is underloaded (with old over-oxidised sludge). The actuation recommended is increase wasting rates. Otherwise, a nutrient deficiency is the cause inferred and the action would be to add nutrients.

When the observation of activated sludge in the microscope shows a normal presence of active protozoa and a predominance of flagellates organisms, then an organic overloading (young sludge under-oxidised causing too high F/M ratio and very low MCRT, lower than 2 d) in the biological reactor is the most suitable cause. This overloading causes a young, under-oxidised sludge (low MCRT due to excess wasting, less than 2 d, lower even if the organic load is readily biodegradable) (also called straggler floc). The amoebae and free-swimming ciliates are also abundant, the floc is weak and spongy and there is presence of turbidity in the settling test (slow settling mixed liquor leaving light fluffy straggler floc in clear supernatant). Organic overloading (and young sludge) actuations entail checking for the value of MLSS, influent composition and wasting rates. Decrease sludge wasting rates to increase MLSS. If batch wasting, avoid wasting when the BOD loading is increasing. If the relation between organic load and biomass concentration is inadequate, reduce wasting/increase MLSS to compensate for heavier loading. Include BOD load from side-streams in F/M calculations. Maintain a level of DO between 2 and 3 mg/l. Possible addition of chemicals to support sludge sedimentation.

When the observation of activated sludge in the microscope shows a normal presence of active protozoan but the flagellates organisms are not predominant, then the presence of white scum on the surface of the aeration basin decides if the cause is the presence of surfactants or not. If there is no presence of white scum, the cause of dispersed growth could be one of these three: exo-cellular polymer production deficiency, temperature of the mixed liquor greater than 35-centigrade degrees or the presence of slowly biodegradable surfactants (if the presence of white scum on the surface of aeration basin is evident). Surfactants presence actuations involve improving the pre-treatment (grit removal).

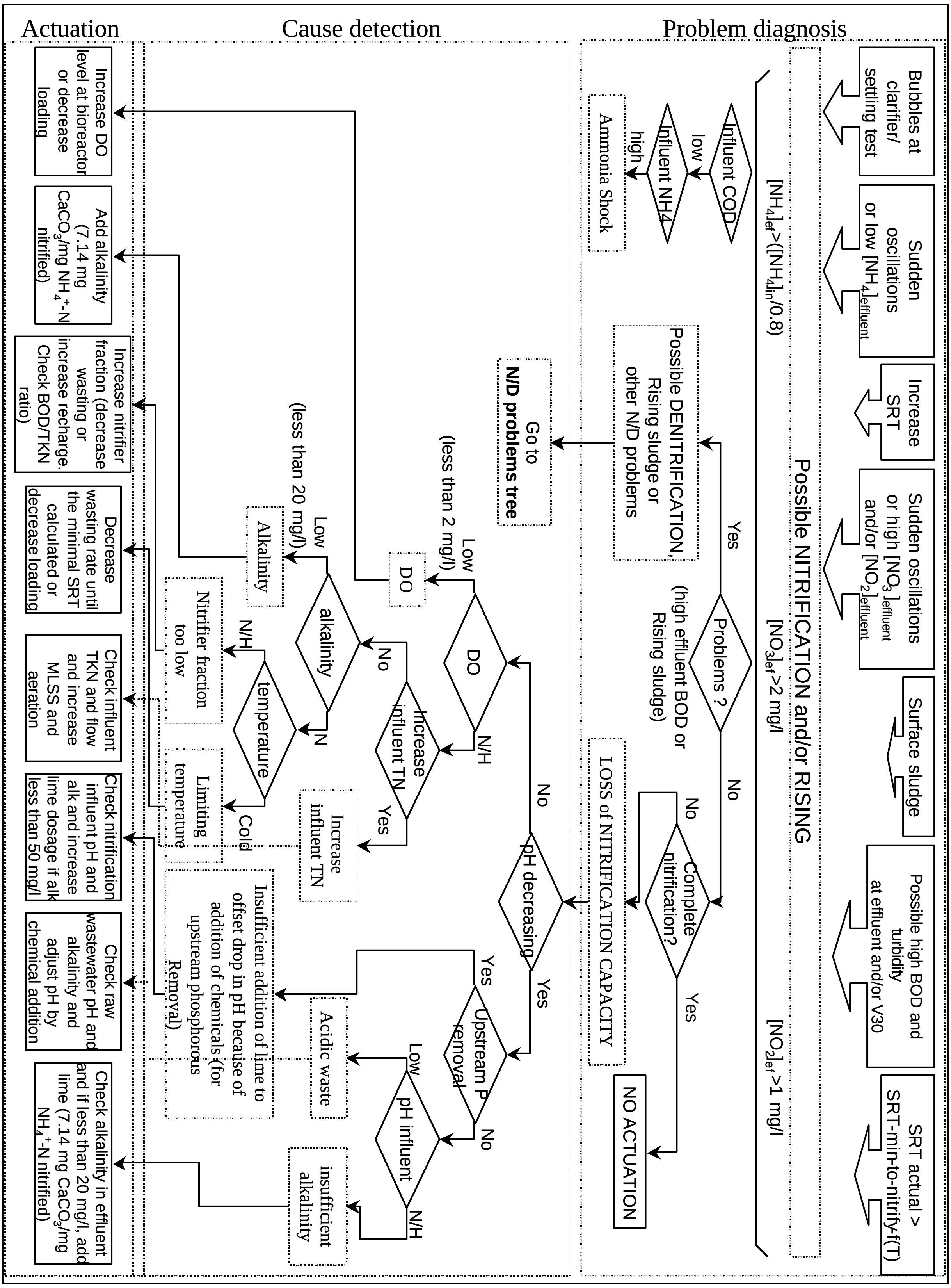
Cause detection and actuation for pin point

When the activated sludge presents the Pin-point floc problem, there is a formation of small, compact, weak and roughly spherical flocs (microflocs), the greater of which settle quickly but the smaller "aggregation" settle very slowly. Sludge is granular rather than flocculent. There is not a good flocculation of smaller flocs, due to the total absence of filamentous organisms, which finally end up rising to the clarifier surface and this is the reason for which this phenomenon gives a cloudy, turbid effluent although the sludge volume index used to be a low value (< 100 ml/g). Supernatant of settling test is moderately turbid with fine, pinpoint floc (about the size of a pin head) in suspension. The solid-liquid separation is inefficient with small flocs escaping to the effluent. The breaking of these existing small flocs can lead to dispersed growth. The breaking or deflocculation of small existing flocs, could lead to dispersed-growth. There is a too much vigorous aeration method (high mechanical shacking) making an excessive turbulence that breaks the flocs.

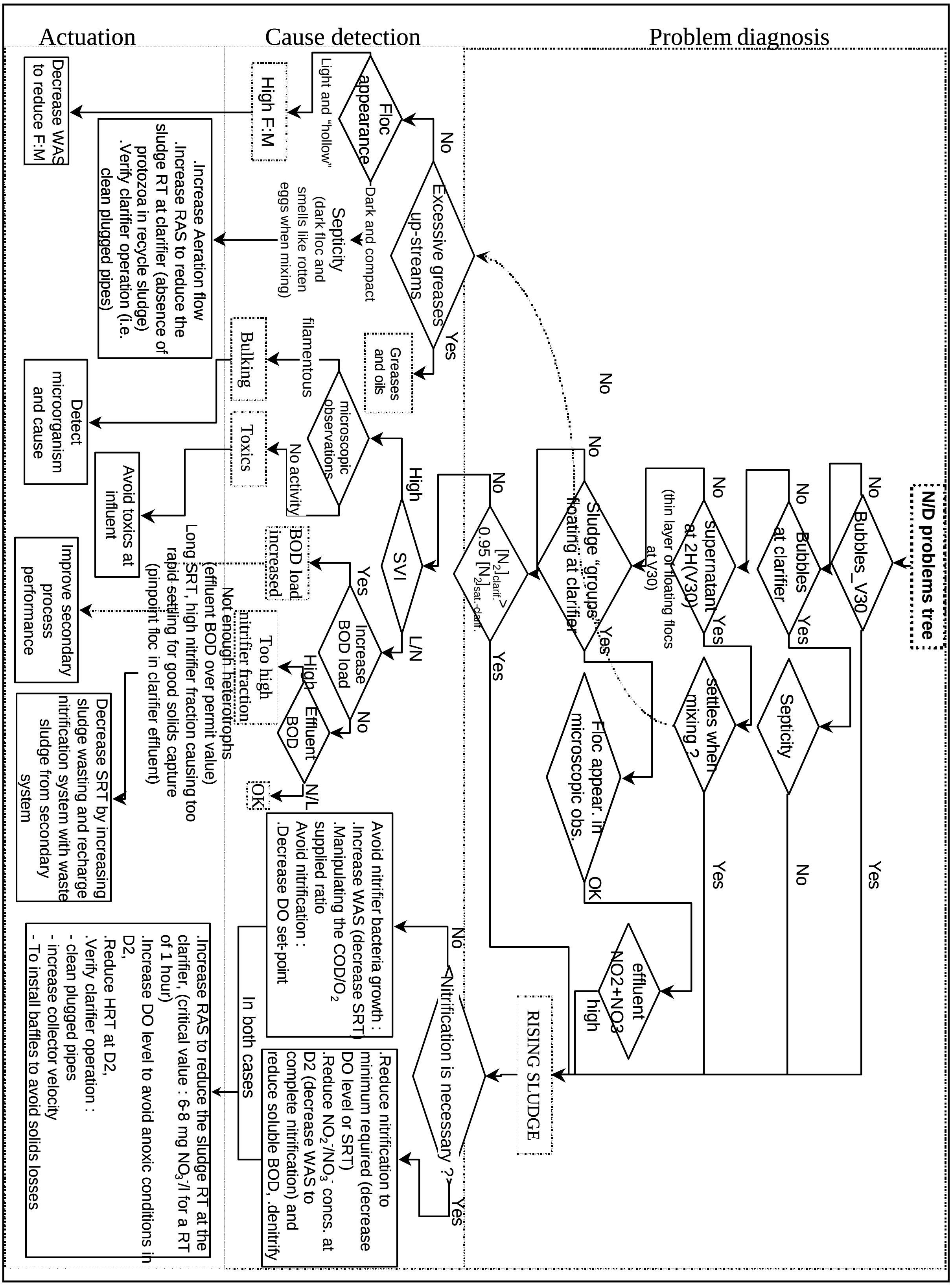
To distinguish among the different causes of the pin-point floc problem, the expert system checks for the DO level on the aeration basin. If the DO level is high, then the pin-point floc is due to an over-aeration. The system checks for DO and decrease aeration or stirring velocity, if lowest DO reading in aeration basin is more than 4.0.

If the DO level is normal or low, then the cause is an underloading aeration basin due to an old sludge too much oxidised. This produces an ash-like material on surface settling test. If stir this floating floc, it does not release bubbles nor settle (mixed liquor had settled very quickly, leaving particles in suspension). (rejecting excessive grease: above 15% of MLSS by weight: improve upstream in-plant grease capture and identify grease dischargers), (if it releases bubbles and settles: beginning of denitrification: RISING). This phenomenon is also called *ashing* and it is caused by an extremely low F/M (lower than in an extended aeration) and old, over-oxidised sludge, which settles quickly but does not flocculate. An old activated sludge could presents too high nitrifying organisms fraction provoking too fast sedimentation due to a very good solids capture. The microscope observations illustrate sessile, rotifer and higher organisms abundance and a dense, dark and compact floc. Floating sludge is encountered in settling tests. Old sludge actuations demand checking for the MCRT (normally, should not be longer than 9 days), increasing sludge wasting flow rate to reduce MCRT and adapt the right F/M ratio. If the *ashing* problem is significant enough to affect the effluent quality, increase wasting rate to raise F/M and diminish SRT.

DECISION TREE FOR NITRIFICATION/DENITRIFICATION SYSTEM



DECISION TREE FOR NITRIFICATION/DENITRIFICATION SYSTEM (Cont.)



Nitrification/Denitrification Problems

This is a decision tree for detecting problems for a nitrification system. These problems relate mainly to loss of nitrification capacity and uncontrolled denitrification in secondary settlers (rising). The undesired denitrification in the secondary settler produces bubbles of N_2, which stick to sludge particles and rises groups of sludge to the clarifier surface, even if the sludge settles correctly. These floating groups of sludge are brown and do not smell bad.

Indicators/Symptoms

There are different conditions that could indicate possible N/D problems. This set of signs includes: effluent ammonia concentration decreasing, high or increasing effluent nitrate and/or nitrite concentration, possible high effluent BOD or turbidity, a high or increasing SRT, the presence of rising sludge within 2 hours in the 30 minutes-settling test and in the clarifier surface and presence of bubbles in the settling test or in the clarifier surface. All these signals launch an intermediate alarm of possible nitrification, which will invoke the diagnosis rules for this operational problem.

Diagnosis

Key variables and order: high BOD effluent or rising sludge, nitrification, bubbles at V30-settling test, bubbles at clarifier, supernatant within 2 hr. at V30-settling test, supernatant at clarifier, floc appearance and effluent NO_x.

The diagnosis process starts when the operator has introduced the results of his/her determinations into the system. In this case, starts identifying whether the plant presents problems of sedimentation (checking for BOD removal or rising sludge). In affirmative case, the rising sludge rules will be launched. In negative case, the next query will ask about whether complete nitrification is attained or not. If effluent total nitrogen is lower than 15 mg/l and effluent NO_x lower than 2 mg/l, there is no problem at all. On the other hand, if nitrification is partial, the system will try to identify the causes of this loss of nitrification capacity.

Diagnosis, cause detection and action plans for rising

In case the system present problems of sedimentation either in the V30 settling test as well as in the clarifier, the system will check for possible denitrification in secondary settler. To identify a hypothetic rising situation, a set of queries must be done in the next order:

- the presence for bubbles in the V30-settling test clearly indicates release of nitrogen gas produced by denitrification. So, the rising situation is obvious.
- If there are no bubbles in the settling test; they are searched directly in the clarifier. If there exists and septicity of wastewater has been rejected, again the rising situation is inferred.
- If there no exists bubbles in the settling test neither in the clarifier, the presence of supernatant within 2H at the V30-settling test is searched (thin layer of floating flocs at the V30-settling test). If there exists a supernatant after 2 hours of starting the settling test, then the ES checks whether this floating sludge settles when stirring or not. If it settles, denitrification is occurring in the clarifiers. If this floating sludge does not settle, the system asks for the possible existence of excessive greases in the influent or primary effluent (upstreams). If there exits, the supernatant is assumed to be greases and fats. If there no exists, the inference engine checks the activated sludge floc appearance. If it seems weak and "hollow", then the problem is assigned to be a high F/M and its corresponding actuation is launched (decrease WAS to reduce F:M). If underside of floc is dark or obnoxious odours are released when sludge is stirred, septicity is occurring. Whenever the sludge residence time at the bottom of clarifier is too much large, e.g. due to bad operation of the collecting scraper of the bottom, sludge becomes anaerobic or as a result of anaerobic conditions in the aeration basin. This fact causes production of bubbles of different gases (SH_2, CO_2, H_2), which, rise black and odorous sludge flocs to the surface and could produce effluent turbidity. Septicity actuations include: Pre-aerate upstream, add an oxidizing agent such as chlorine or air to the influent, increase aeration flow, increase RAS to reduce the sludge detention time in clarifier (critical value: 2 hr) (absence of protozoa in recycle sludge) and verification of clarifier operation (i.e. clean plugged suction pipes or repair or replace damaged flights).
- If supernatant is not detected in the V30 settling test, then the ES looks for the presence of groups of sludge floating on the clarifier surface. If they exist, the microscopic observation of floc appearance indicates a good and well-formed activated sludge floc and effluent NO_x is high, then rising is diagnosed again.
- Finally, the last clear signal of rising is a nitrogen gas concentration in the secondary clarifier greater than the saturated nitrogen gas concentration*0.95.

If the rising situation has been inferred the actuation plan varies according if nitrification is required or not. If the wastewater system must remove nitrogen, then actuations are: reduce nitrification to minimum required, reduce nitrite and nitrate concentration at the clarifier (decrease WAS to complete nitrification and reduce soluble BOD), denitrify or improve denitrification system. If the wastewater system is not requested to make N removal, then actuations are: avoid nitrifier bacteria growth (gradually increase wasting rate to stop nitrification -decrease SRT-, manipulating the COD/O_2 supplied ratio and decrease DO set-point). Anyway, in both cases, one should take any of the following preventive actions: Check for effluent nitrates (critical nitrate concentration values at the clarifier at 20ºC are about 6-8 mg $N\text{-}NO_3^-$ and critical hydraulic residence time is about 1 hour, denitrification is likely if nitrates exceed 10 mg/l), increase RAS to reduce the sludge detention time in clarifier, increase DO at the aeration tank, reduce hydraulic retention time at clarifiers, verify clarifier operation (clean plugged suction pipes and increase collector speed, if possible), reduce number of clarifiers on line to shorten detention time, increase collector velocity, improve and complete denitrification and install baffles to avoid solids losses (non-specific method).

If the process presents slow settleability (SVI>150) and there is a numerous presence of filamentous organism, then the problem is due to filamentous bulking (Bulking actuation is proposed). Otherwise, if the SVI is greater than 150 but the microscope shows no or few activity of the protozoan, then the presence of toxic waste is inferred as the most probable cause (toxic actuation is proposed). If this nitrifying activated sludge settles correctly, then the expert system checks for an increase influent BOD loading. If it is certainly detected, the problem should be corrected improving the secondary process performance. On the other hand, if there is an increasing or high value in the effluent BOD but there is not an increased BOD load, then the high effluent BOD (maybe over the permit value) is assumed to be due to a too high nitrifier fraction (long SRT) causing too rapid settling for goods solids capture (there are not enough heterotrophic microorganisms). This situation can lead to pin point floc in clarifier effluent. The actuation proposed in this case involves to decrease SRT by increasing sludge wasting, decrease the nitrifier fraction and improve solids capture by recharging nitrification system with waste sludge from secondary system. Last, if there is not an increased BOD load neither a high BOD effluent, then the system infers that the process is being well operated and that there is no problem at all.

Diagnosis, cause detection and action plans for loss of nitrification

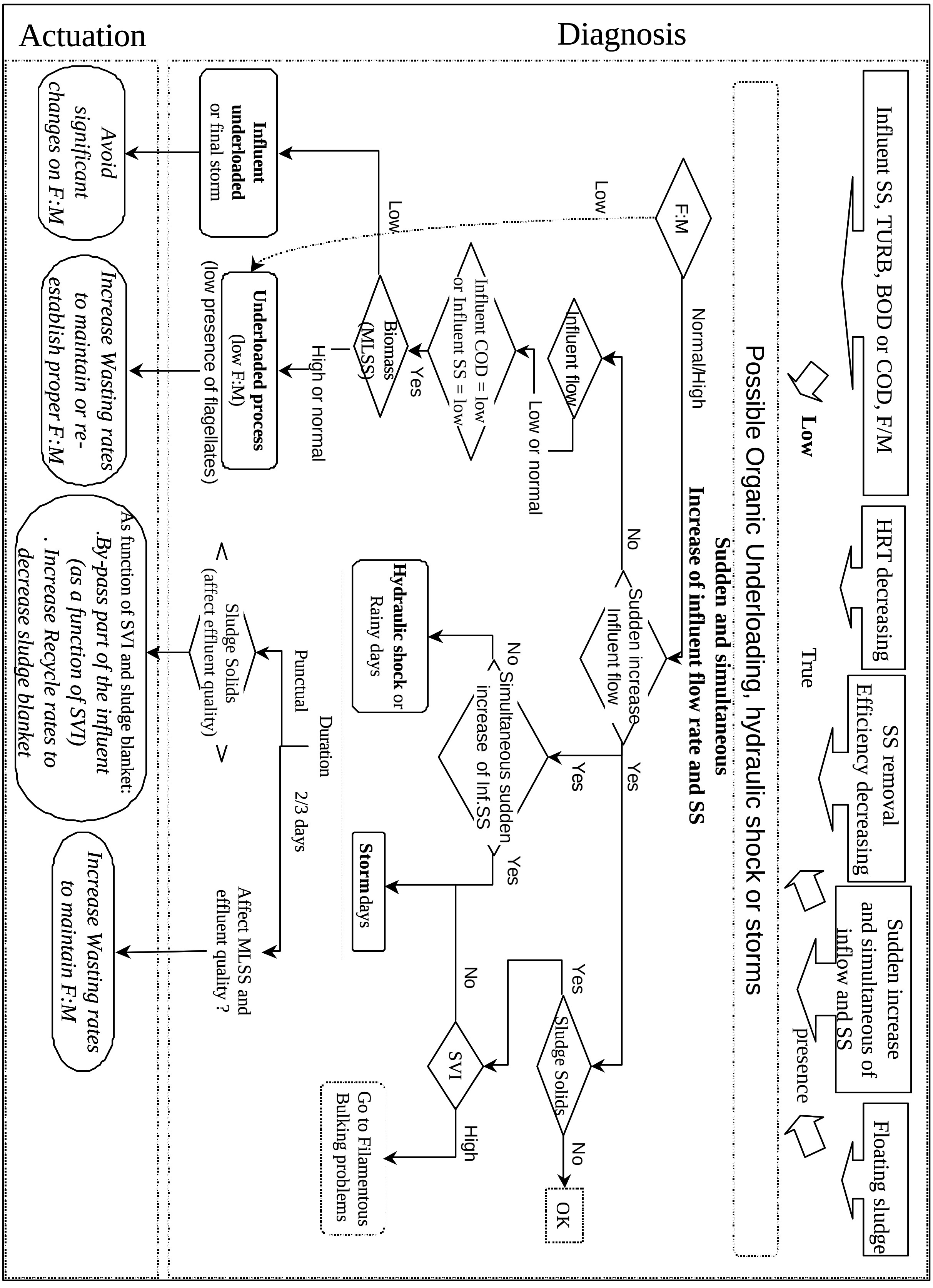
In case the system has inability to completely nitrify or experiments a loss of nitrification, then the system checks for the probably cause. Sometimes the effluent ammonia level exceeds the permit value.

First of all, a decreasing in nitrification system pH is tested. If it occurs, then the loss of nitrification is due to an alkalinity deficiency or to a too low pH. To clearly distinguish, the ES checks if the plant makes an upstream phosphorous removal. If it is true, then the loss of nitrification is due to an insufficient addition of lime to offset drop in pH because of addition of chemicals for P removal. The P removal actuations include checking for influent pH and alkalinity. If alkalinity is less than 50 mg/l, increase lime dosage. If there no exists upstream chemical P removal, the system checks for the influent pH. If it is normal or a little high, then the loss of nitrification is due to insufficient addition of lime to offset alkalinity destruction during nitrification. The ES must check for alkalinity in the clarifier effluent. If it is less than 20 mg/l, then start addling lime to nitrification system (also others alkaline agents such as sodium carbonate, caustic soda can be added to the aeration tank influent). If the influent pH is low, then the loss of nitrification is due to a too low ML pH. This can be produce by the addition of acidic wastes to sewer system. Low pH actuation involves checking for raw wastewater pH and alkalinity and mixed liquor pH, increasing pH with alkaline source (adding an alkaline agent such as sodium carbonate, caustic soda or lime to the aeration tank influent) and enforcing sewer-use ordinance.

If a pH decreasing is not experimented in the aeration basin, alkalinity, DO, cold temperatures, a TN increase load and a low nitrifying fraction are going to be explored as the possible causes. First, the DO level at aeration tank is explored. If it is low, then the limiting factor to completely nitrify is the DO concentration. The DO actuation checks for the DO level (minimum DO in nitrification system should be 3 mg/l or more). Increase aeration or decrease loading on nitrification tanks, as necessary. If the low DO is not the cause, a high TN concentration in the influent is checked. If there has been an increasing in total daily influent nitrogen loads, then this is the cause of not getting a complete nitrification. The high TN actuation will check for influent flow rate and TKN concentration, increase the MLVSS in nitrification tanks by increasing concentration or putting additional nitrification tanks on line and increase aeration. If there has no been and increasing in influent NT load, then the influent alkalinity is checked. If it is low, the problem is that there is no enough alkalinity in raw water to offset pH drop. The system will recommend to increase alkalinity (raise pH by adding an alkaline agent such as sodium carbonate, caustic soda or lime to the aeration tank influent), operate first bay of nitrification tank in anoxic mode, if possible, to increase alkalinity and check for chemical addition equipment. If influent alkalinity is not low, the ES checks the ML temperature. If it is cold, this is the limiting factor to allow complete nitrification. Temperature actuation involves checking for nitrification rate and MLVSS, decreasing loading on nitrification system, or increasing biological population (MLVSS) in nitrification tanks by raising MLVSS concentration or adding nitrification tanks. Finally, if the temperature is not the problem, then the cause of not be able to completely nitrify should be a too low nitrifier fraction in nitrification tanks. This low nitrifier fraction can be provoked by any of these three causes (each one with its corresponding actuation):

- biological solids are escaping in effluent: add polymer to nitrification clarifier to enhance settling of biological solids
- too high sludge wasting: decrease wasting sludge from nitrification system or increase recharge
- BOD/TKN ratio inadequate in secondary effluent, if two-stage process: if BOD is higher than normal, increase first-stage system SRT.

DECISION TREE FOR UNDERLOADING PROBLEMS



Underloading Problems

This is a decision tree for detecting underloading situations in the aeration tank. These situations can be caused by rainy days or storms, by an underloaded influent or by a too high biomass concentration or by a hydraulic shock. Impacts due to increased hydraulic loading can be summarised in increase in sludge handlings from primary treatment, decrease in removal efficiencies, and sludge blanket overflows in the plant effluent.

Indicators/Symptoms

There are different conditions that could indicate a possible underloading situation. This set of signs includes:
Low values of TSS, COD, BOD or turbidity at the influent, a lower HRT at the aeration tank, a lower primary treatment efficiency, a sudden and simultaneous increase in inflow and suspended solids, and floating sludge. All these signals launch an intermediate alarm of possible underloading, which will invoke the diagnosis rules for these operational problems.

Diagnosis, cause detection and actuation

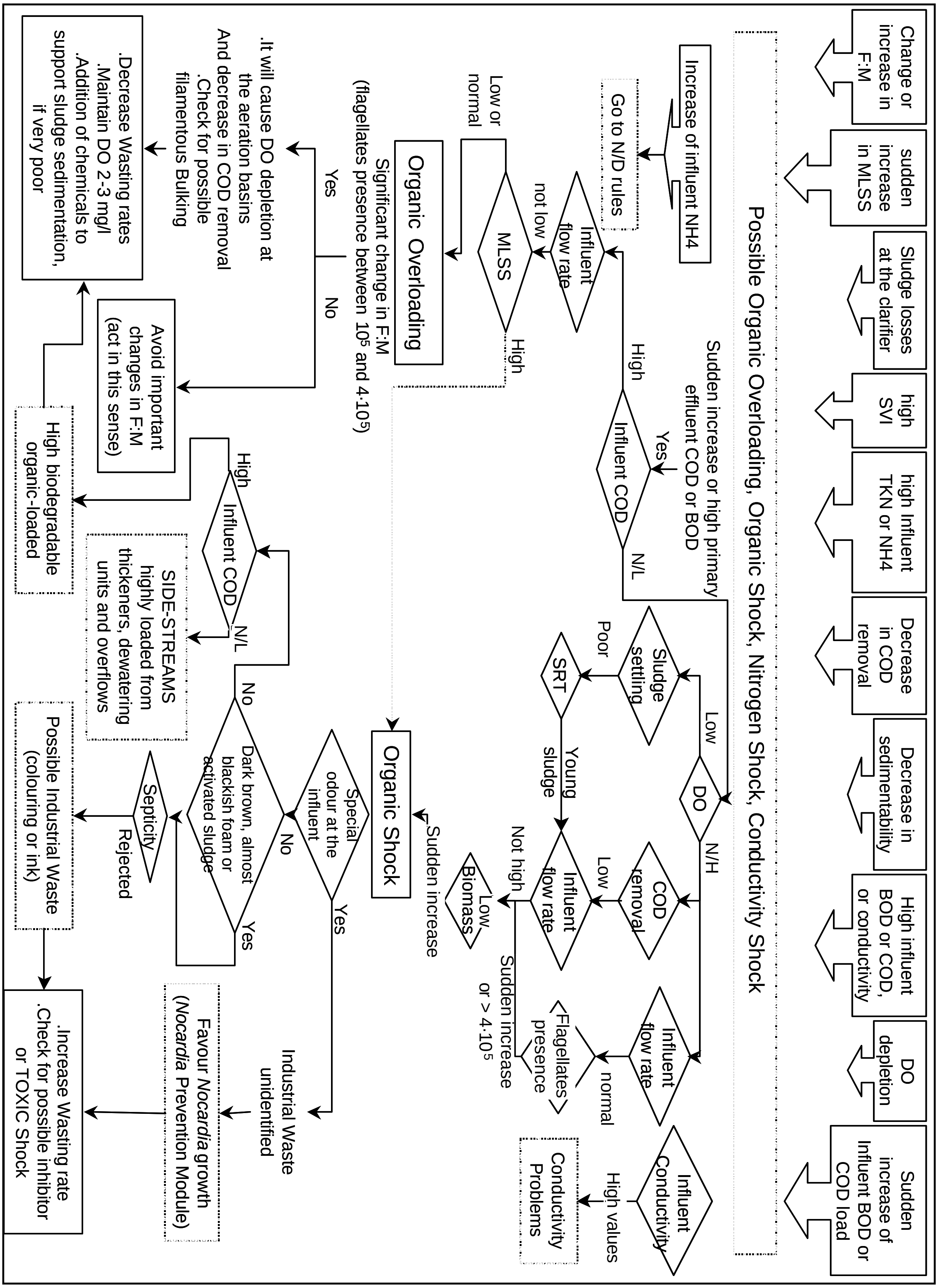
Key variables: influent water flow rate, COD and TSS, sludge floating, biomass concentration

The diagnosis process starts when the operator has introduced the results of his/her determinations into the system. In this case, starts checking for a sudden and simultaneous increase in the inflow rate and TSS. If there exists a sudden increase in influent flow rate and TSS, then the situation of storm is directly diagnosed. Also with a sudden increase in flow and TSS and, if sludge floating in the secondary clarifier is viewed, then if the activated sludge presents high values of SVI, then the alarm of possible filamentous problems must be launched. For normal or low values of SVI, the storm situation is inferred again. The storm/hydraulic shock actuation depends on its duration:

- If the storm is punctual and affects the clarifier (loss of solids by peak flows, more probably with high SVI), then it is recommended to by-pass part of the inflow (the quantity is function of the SVI and the sludge blanket level) and to increase recycle rate.
- If the storm (or rainy days) takes more than 2 days and affects considerably to the MLVSS concentration and effluent quality, then the actuation would consists in take care for the remaining sludge. It means to increase wasting sludge rates to compensate the lighter loaded influent.

If there no exists a sudden increase in influent flow rate and TSS but the influent flow rate is low or normal, then the influent COD and TSS concentrations are checked. If they have low values, and biomass concentration is low, then the situation inferred is a possible-storm-end or, most probably, an underloaded influent (low organic-loaded influent). The action plan is centred in avoiding significant changes on F:M. On the other hand, if the influent COD and TSS concentrations are low and biomass concentration is high or normal, then an underloaded process is diagnosed. The underloaded actions consist of increasing the wasting flow rate to maintain or re-establish proper F:M. In all the underloading situations, the microbiological process experiences a too low F/M values and therefore, the risk of filamentous proliferation resulting in severe bulking or foaming episodes is really at hand.

DECISION TREE FOR OVERLOADING



Overloading Problems Definition

This is a decision tree for detecting overloaded situations in the aeration tank, organic shocks, nitrogen shocks (ammonia peaks), industrial wastes and conductivity shocks.

Indicators/Symptoms

There are different conditions that could indicate a possible overloading situation. This set of signs includes:
Sudden F/M increase, sudden biomass increasing (500 mg/l in 2 days) and COD removal efficiency lower than 80%, sudden BOD or COD influent increasing, high SVI, loss of solids in effluent, decrease in removal efficiency (rejecting inflow peaks) and in settleability, inflow increase, high influent ammonia concentration, high influent conductivity and DO depletion. All these signals launch an intermediate alarm of possible overloading which will invoke the diagnosis rules for these operational problems.

Diagnosis

Key variables: primary effluent COD and BOD, DO, influent flow rate, biomass concentration, COD removal, influent ammonia and F/M.

The diagnosis process starts when the operator has introduced the results of his/her determinations into the system. In this case, starts checking for a sudden increase in the primary effluent COD or BOD variables and in the biomass concentration. If there exists a COD or BOD sudden increase, the influent COD is high (more than 450 mg/l), the influent flow rate is not low and biomass concentration is not high, then an Organic overloading in the aeration basin is detected. The organic overloading actuations suggested depends on whether the F/M ratio is significantly affected or not. If it is greatly affected, decrease wasting flow rates to offset the increased loading, maintain DO 2-3 mg/l, add chemicals to support sludge sedimentation (if very poor) and check for possible Bulking (filamentous organisms trend). If F/M ratio is not significantly affected, act in this sense, that is, avoid important changes in F:M.

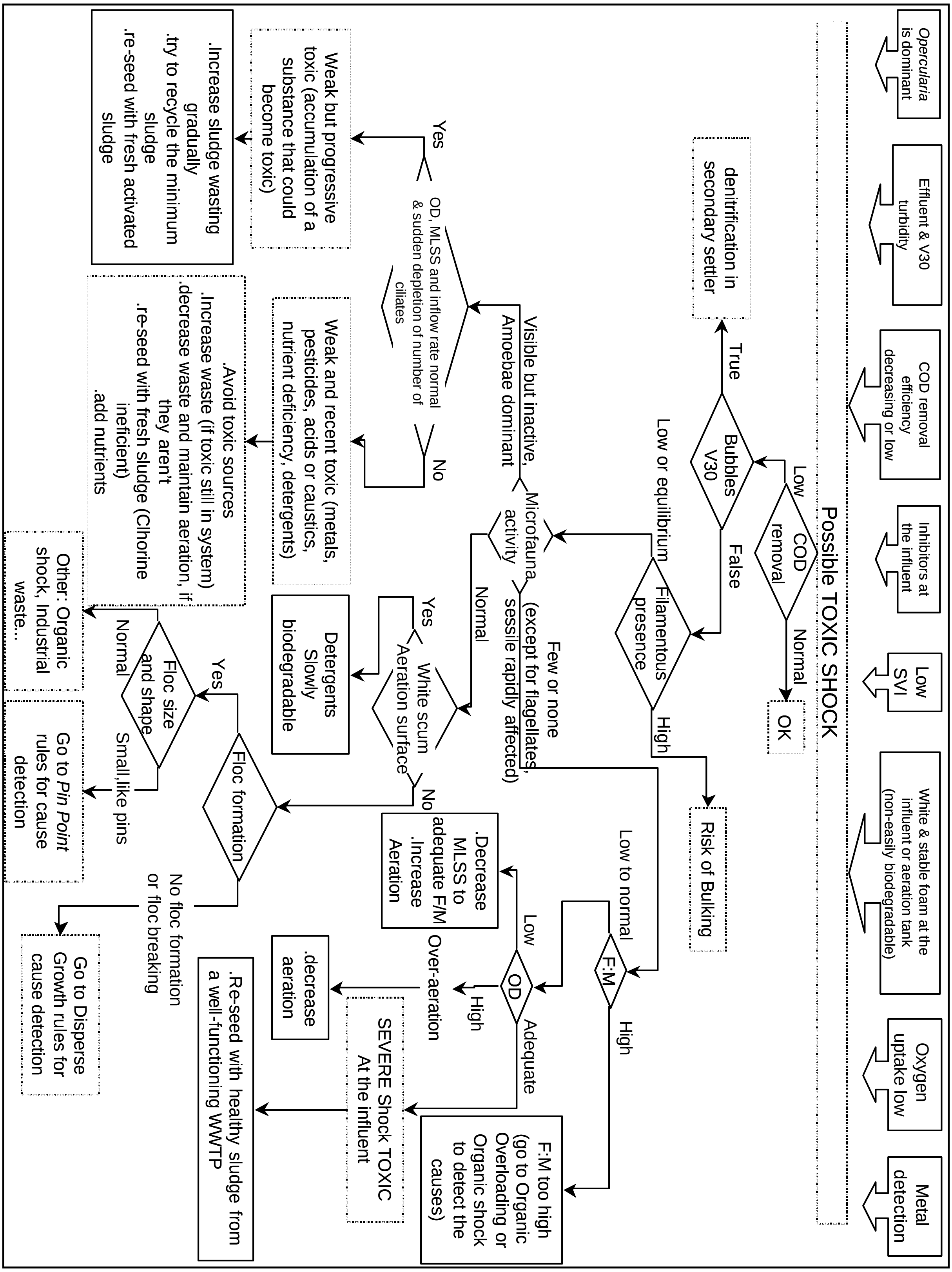
On the contrary, if there exists a COD or BOD sudden increase but the influent COD is not high, then the inference follows other paths to detect organic shocks. First, DO is checked. If DO level is not high, COD removal is low, influent flow rate is not high and biomass concentration has suffered a sudden increase, then an Organic shock can be concluded as the most suitable problem. A second path to diagnose the organic shock, evaluates the influent flow rate after the DO low or normal level. If the influent flow rate is normal and the population of flagellates suffers a sudden increase (or they are > $4 \cdot 10^5$) as well as the biomass concentration, the organic shock is also detected. Finally, a third path can also conclude an organic shock episode. This route explores the sludge settling ability, the SRT and then, the inflow rate and biomass concentration. This will cause a variation in the OUR and probably a decrease in removal efficiency.

Once the organic shock is identified, the expert system tries to infer the possible cause. In Granollers, there are three main causes, which can be distinguished by means of the existence of special odour, presence of dark brown scum (rejecting septicity) and the evaluation of influent COD :

- High organic easily biodegradable substrate in the influent: decrease Wasting rates, maintain DO 2-3 mg/l, addition of chemicals to support sludge sedimentation (if very poor).
- High loaded side-streams, specially coming from thickening and filtering units: identify the overloaded source and improve that unit performance.
- Industrial wastes identified or not : If dark-brown scum (almost black) or dark-brown mixed liquor are detected (rejecting septicity), then an organic shock caused by an industrial waste is inferred (ink or colouring). In both cases, increase wasting rate and check for possible inhibitor or toxic.

If a high influent ammonia concentration is detected, then a situation of ammonia peaks is inferred and the N/D rules are launched. Finally, if a value of conductivity in the raw wastewater exceeds the maximum values, then a shock of salinity is inferred.

DECISION TREE FOR TOXIC SHOCK



Toxic shock
This is a decision tree for detecting toxic shocks situations in the aeration tank. We can distinguish three kinds of toxic wastes: recent and light (but punctual) toxic shock, severe toxic shock and light but gradual and continuous toxic shock.

Indicators/Symptoms
There are different conditions that could indicate a possible toxic shock situation. This set of signs includes:
High values of turbidity at the effluent and V30 settling test, a low SVI value, a lower COD removal efficiency, the presence of white scum, a lower or decreasing OUR, presence of metals, presence of inhibitors, an abundant presence of *Opercularia spp.* All these signals launch an intermediate alarm of possible toxic shock that will invoke the diagnosis rules for these operational problems.

Diagnosis process.
Key variables: COD removal efficiency, presence of bubbles at V30 settling test, presence of filamentous organisms, microfauna activity, F/M, DO, MLSS, inflow rate.

The diagnosis process starts when the operator has introduced the results of his/her determinations into the system. In this case, starts checking for the efficiency of biological COD removal. If the COD removal efficiency is low (effluent COD/influent COD > 0.2) (less than 80% of removal) and there are no bubbles in the V30 settling test, then the qualitative presence of filamentous organisms is checked. If it is high, a possible Bulking situation must be checked. The ES invokes the Bulking risk module. If the filamentous are no or few present or in equilibrium with floc-forming bacteria, then the microfauna activity is checked.

If there are no or few protozoa present (maybe, except for flagellates because protozoan dye rapidly, first sessile ciliates), the F/M ratio is checked. If F/M has a high value, the problem (cloudy secondary effluent) is caused by a too high F/M (organic overload). The overload actuations should be to reduce wasting flow rates, check for DO level in aeration tank and adjust to 2 to 3 mg/l and add settling aid, if necessary. If the F/M ratio is low to normal and the DO level is correct, then the situation inferred is a severe toxic shock at the aeration basin. A metal or bactericide has entered the plant by the influent and is causing the dead of protozoa and therefore, decreasing the biological biodegradation. In this case, re-seed the plant with healthy sludge from another well-operated plant or add freeze-dried microorganisms. If the DO level is low, then reduce MLSS to proper F/M and increase or balance aeration. Finally, If the DO level is high, the process is over-aerated. The over-aeration disperses mixed liquor and can form pin-point floc. Actuation: Reduce aeration.

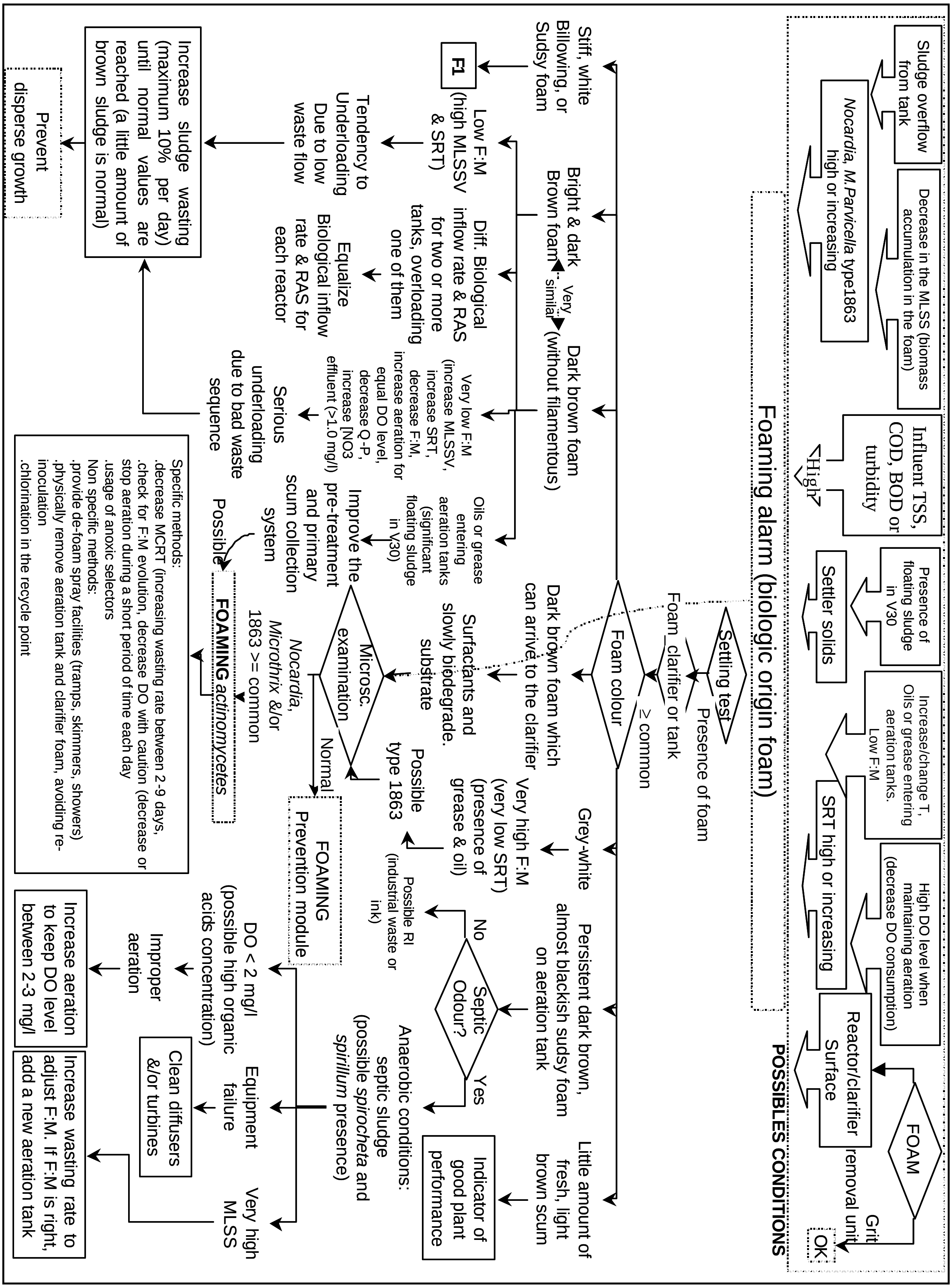
If there is no or few activity but the protozoa are still present (*amoebae* predominant), then this problematic situation is caused by a recent light toxic load (heavy metals, acids, caustics or pesticides). If the DO level, the Biomass concentration and the inflow are normal and the current number of ciliates is lower than the 75 % of the number of ciliates of 2 days before, then we can conclude that this light toxic load is currently occurring. This is a gradual accumulation of a substance that could reach to be a toxic concentration. The actuations should include identify and eliminate source of toxic load, enforce sewer use ordinance to eliminate toxics, waste sludge gradually, try to recycle the minimum and re-seed the plant with healthy sludge from another well-operated plant or add freeze-dried microorganisms.

On the contrary, if the DO level, the Biomass concentration and the inflow rate are not normal and the current number of ciliates is normal, then a weak and recent toxic shock is inferred. The action plan include identify and eliminate source of toxic load, enforce sewer use ordinance to eliminate toxics, waste sludge gradually, try to recycle the minimum, re-seed the plant with healthy sludge from another well-operated plant or add freeze-dried microorganisms. If toxics still present, continue normal wasting or increase wasting to purge the system. If toxics have passed through system, get seed sludge and stop wasting until microorganisms built up.

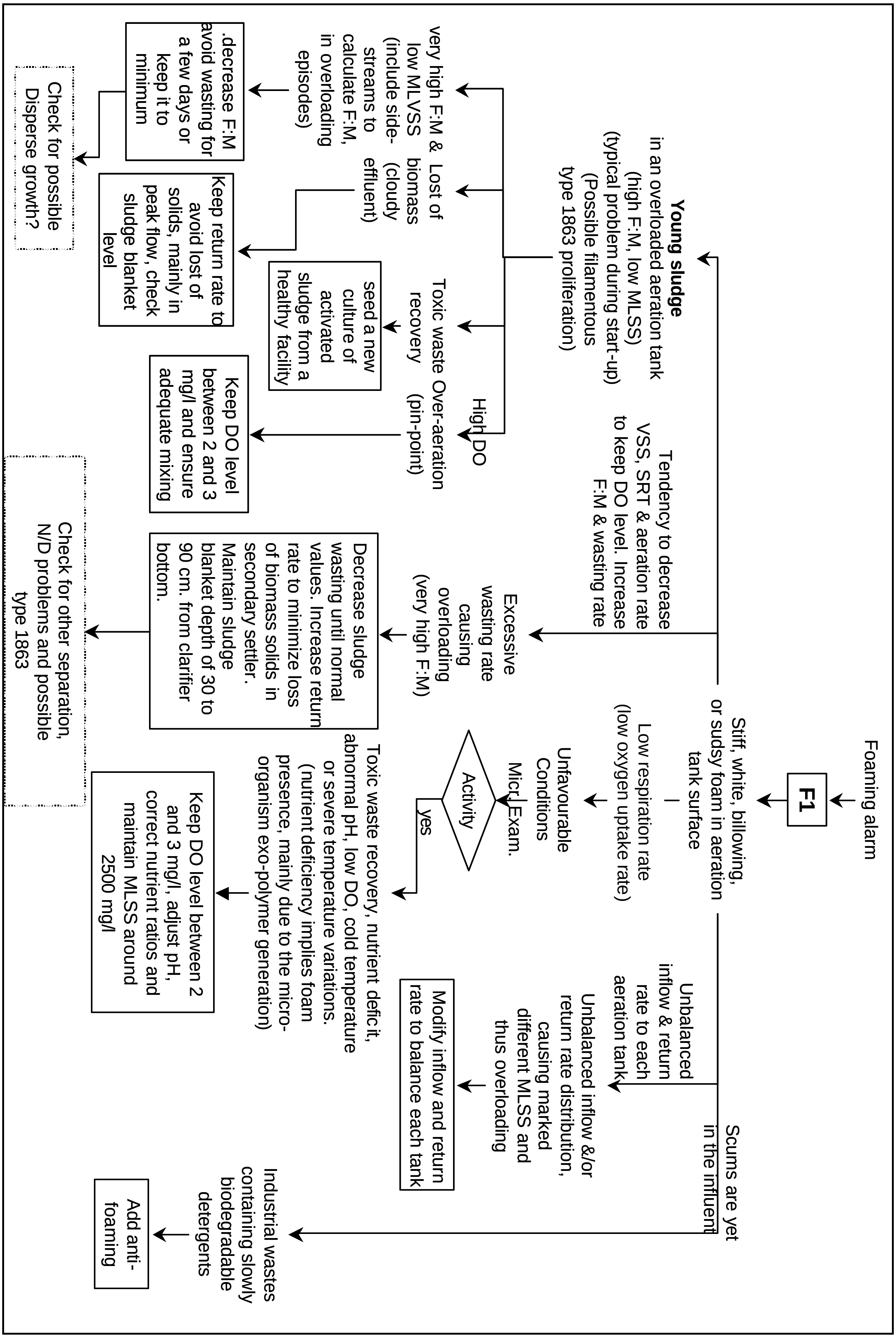
If protozoa are present and active, and there is white scum at the aeration surface, detergents slowly biodegradable are the cause of the toxic effects. If protozoa are present and active, there is no white scum at the aeration surface and the activated sludge floc is dispersed (with either slow or fast settling), then the toxic waste will easily cause dispersed growth. On the other hand, if small and thin flocs are formed, pin point problem can be achieved. If normal flocs are formed, other problems should be checked (organic shock, industrial wastes…).

A settling aid always can be added to relieve symptoms while the underlying problem is being corrected.

DECISION TREE FOR FOAMING DIAGNOSIS



DECISION TREE FOR FOAMING DIAGNOSIS (Cont.)



Foaming Definition

The foaming term refers to highly hydrophobic foams caused by the proliferation of filamentous organisms. These foams are very stable and float in the aeration surface because they are formed by air bubbles trapped in the flocs and prevent them to settle. These foams do not appear suddenly but they take 2/3 days to give a problematic situation. Foaming scum give operational problems like losses of sludge solids, suspended solids capture in the scum (up to 30% of the biomass), causing a loss of SRT control and sludge treatment problems.

Indicators/Symptoms

There are different conditions that could indicate a possible foaming situation. This set of signs includes :
higher values of COD, BOD, TSS and Turbidity at the effluent than the normal, the presence of floating sludge in the 30 minutes-settling test and in the clarifier surface, a decrease in the MLSS (biomass accumulation in the foam), a high or increasing value for SRT, the presence of brown and/or white-grey scum, a low value for F/M, the presence of oils or greases at the biological influent, a presence of *Nocardia*, *Microthrix* or type 1863 greater or equal than abundant, a great or increasing presence of *Nocardia*, *Microthrix* or type 1863, a lower OUR, the presence of foams at the clarifier/aeration basin surface and a high DO level. All these signals launch an intermediate alarm of foaming, which will invoke the diagnosis rules for this operational problem.

Diagnosis

Key variables and order: presence of foam in the settling test and clarifier, colour of foam

The diagnosis process starts when the operator has introduced the results of his/her determinations into the system. In case the qualitative information of the settling test is available, then the rule-based system will check for the presence of foam in the aeration basin.

If there exists **dark tan foam** on the aeration basin (that is strong, carries over to the clarifier and is difficult to break mechanically) and the microscopic examination for filamentous microorganisms confirms an excessive presence of actinomycetes (*Nocardia)*, *Microthrix Parvicella* or type 1863, then FOAMING situation is inferred. In fact, if the scum has a more grey-white colour, then the filamentous organism type 1863 is the responsible of the scum. It is thought that this filamentous is favoured by a too high F/M ratio (maybe caused by greases and fats at the influent). If microbiological observations still do not indicate a high but normal presence of actinomycetes, then the risk module of foaming is launched. The foaming decision tree can be launched also from other inferring rules, e.g. from the bulking diagnosis tree.

Cause Detection and Actuation

Two main possible causes of foaming (*Nocardia and Microthrix Parvicella*) are documented and they can be distinguished by checking for the MCRT actual value. If the MCRT value is too long, then this is assigned to be the cause. On the other hand, the nature of substrate (high concentration of slowly or non biodegradable substrates, e.g., possible surfactants resistant to biological degradation, influent and recycled grease and fats) causing a deficient substrate gradient in plug-flow aeration basins (F/M too low). In fact, both causes are very interrelated because an older sludge will favour the decreasing of F/M ratio. The high MCRT actuation involve increasing sludge wasting to reduce MCRT (specific method) whereas the action plan with respect to the nature of the substrate, we can differentiate between:

- preventive (specific) methods: control and removal of influent, secondary influent and recycled greases and fats (surfactants and hydrophobic substrates) (enforce sewer-use ordinance), increase wasting rate to fix SRT values to 2-9 days, check for F/M evolution, decrease aeration with caution (decrease or stop aeration during a short period of time each day), use of anoxic selector, decrease diffused air flow rate, if possible, and use surface aeration instead of diffused aeration; and finally improve pre-treatment processes (grease, fats and oil removal)and primary scum collection systems.
- foaming non-specific methods: provide de-foam spray facilities (tramps, skimmers, showers,...); remove physically foam from aeration tank and clarifiers, do not recycle removed foam and scum through the plant, chlorination at the recycle point. If nitrification is required, use of anoxic selectors can be effective in *Nocardia* control, and aerobic selectors in *M.Parvicella* control at low SRT values (5 days).

With respect to *Nocardia* actuations, it is not easy to remove since it is a filamentous organism with ramifications of small length. It does not have significant effects in the SVI value but forms very stable and viscous scum in the aeration and clarifier surface. *Nocardia* scum are not easily removed mechanically (in winter, they can freeze and, in summer, can odour due to putrefaction) neither respond to chemical anti-foaming reagents. As a preventive method, it is recommended to work at low MCRT values whereas as non-specific methods, we can distinguish:

- Chlorination at the recycle point can be helpful although *Nocardia* is not completely removed because this filament is not usually exposed to chlorine.
- Increasing of wasting flow rate presents some limitations: scum are not removed with sludge and if they are a little removed, they can give problems in the next operational units (digesters…) and the problem can be reactivated by

recycling side-streams, supernatant...and finally, it can affect nitrification. However, if nitrification is not required, increasing of WAS up to SRT values around 2 days could be a helpful solution if it is combined with physical removal from surfaces.

- Use of traps and water showers to remove scum, avoiding continual re-seeding of *Nocardia.*
- Chemical and anti-foaming agents: chlorination (with sprays, 2-3 g.Cl_2/l), coagulants (4 g.Fe/Kg·d) and anti-foaming agents (low efficiency in front of viscous scum).

If there exists **dark brown foam** on aeration tank surface, the cause of foaming is not the proliferation of filamentous organisms but can be an aeration tank approaching or critically underloaded (F/M very low) condition due to improper or insufficient wasting program (this situation can lead to dispersed growth) or scum of oil and grease entering aeration tanks (coming from primary treatment). If the scum are already at pre-treatment and enters the aeration tank coming from primary treatment, then the foaming is due to influent oil and grease and the actuation to carry out is to improve the pre-treatment and primary scum collection systems and enforce sewer-use ordinance. Otherwise, if the scum is not coming from primary treatment, then the underloaded situation causing foaming is due to either a bad wasting sequence or an imbalance between RAS and secondary influent flow rate. If there exists an imbalance flow rates between the secondary influent and return rates in one, then this fact causes underloading in one tank. Underloaded actuation: Check and monitor trends for : increasing MLVSS, SRT, temperatures, aeration for the same DO levels, and secondary effluent nitrate level (above 1.0 mg/l), and decreasing F/M, DO level for the same aeration, wasting rates, and aeration tank effluent pH. Increase wasting rate by not more than 10%/day until process approaches normal control parameter values and a modest amount of light tan foam (typically a sign of well operated process) is observed on aeration tank surface. Expand sludge thickening and handling facilities if necessary; use primary clarifier for temporary sludge storage, if feasible. Underloaded actuation (due to imbalanced flow rates): Check and monitor secondary influent and return rates to each aeration tank, equalise influent and return rates to each aeration tank.

If there exists **dark brown, almost blackish** sudsy foam on aeration tank surface, the cause of foaming is due to anaerobic conditions reached in the tank or to industrial wastes. Also it can be experienced that the MLSS are very dark brown, almost black. We can discriminate between anaerobic conditions and industrial waste if we smell a septic or sour odour from aeration tank. If we don not smell that, then the black foaming is probably caused by an industrial waste and the industrial waste actuation plan is launched. The first actuation suggested is to identify and to eliminate the source of toxic load. In very severe cases, a reseed with activated sludge from another plant or the addition of freeze-dried microorganisms is suggested. If an industrial source is identified, it is needed a pre-treatment in the own industry (enforce sewer-use ordinance). If septic odour is smelled, then anaerobic conditions occurring in aeration tank is concluded. The sludge is becoming septic and there can be observed *spirochete* and *spirillum* bacteria in the microscope. Three main causes are pointed at: low DO, high MLSS and equipment failures. First, the DO level is checked. If it is lower than 2 mg/l, than the cause in an improper aeration (maybe caused by a high organic acid concentration) and the actuation taken is to increase aeration to maintain 2-3 mg/l. Then, the MLSS is checked to detect a too high value. In positive case, the corrective action is to increase wasting rates to adjust MLSS up to proper F/M. If we are at proper F/M, put another aeration tank on line, if possible, to reduce MLSS. Finally, the last cause, a problem in the equipment. The actuation involves to repair leaks or clean diffusers (if diffused air system), clean blades of rags or ice (if mechanical air system).

If there exists stiff, **white**, billowing, or sudsy foam on aeration tank surface, the causes of foaming are diverse. We must study each of them. First, we must check whether the scum are yet in the influent. If they are, then the cause should be industrial wastes with slowly biodegradable tensactives. The actuation suggested is to add anti-foaming and to enforce sewer-use ordinance.

Secondly, the respiration rate is checked. If it is very low (less than 5 mg/g·h), then unfavourable conditions are diagnosed. Also, if there are no signals of microbiological activity, then a highly toxic waste (metals or bactericide) is the probable cause. In this case, the actuation consists in re-establish a new culture of activated sludge. If possible, waste toxic sludge from the process without recycling portions of it back into the process. Seed the process with healthy activated sludge from a well-operating plant and enforce sewer-use ordinance. If normal microbiological activity is showed in the microscope, then this unfavourable conditions can be provoked by any or a combination of the following : a toxic waste recovery, nutrient deficiency, abnormal low or high pH, insufficient DO, colder wastewater or severe temperature variations resulting in reduction of MLSS. The actuation plan includes waste sludge and considering to seed the process with healthy activated sludge from a well-operating plant or using the freeze-dried variety. It is also necessary to identify and correct the problem.

Third, the wasting rate is checked. If it is too high, then this white foam is caused by an excessive sludge wasting causing an overloaded aeration tank (low MLSS). Other possible observations in this situation could be a decreasing MLSS, aeration for the same DO levels and MCRT, and an increasing F/M and wasting rates. The actuations suggested are reduce wasting rate by not more than 10%/day until process approaches normal control parameters. Increase return rate to minimise effluent solids carry-over from secondary clarifier. Maintain sludge blanket depth of 30 to 90 cm from clarifier floor.

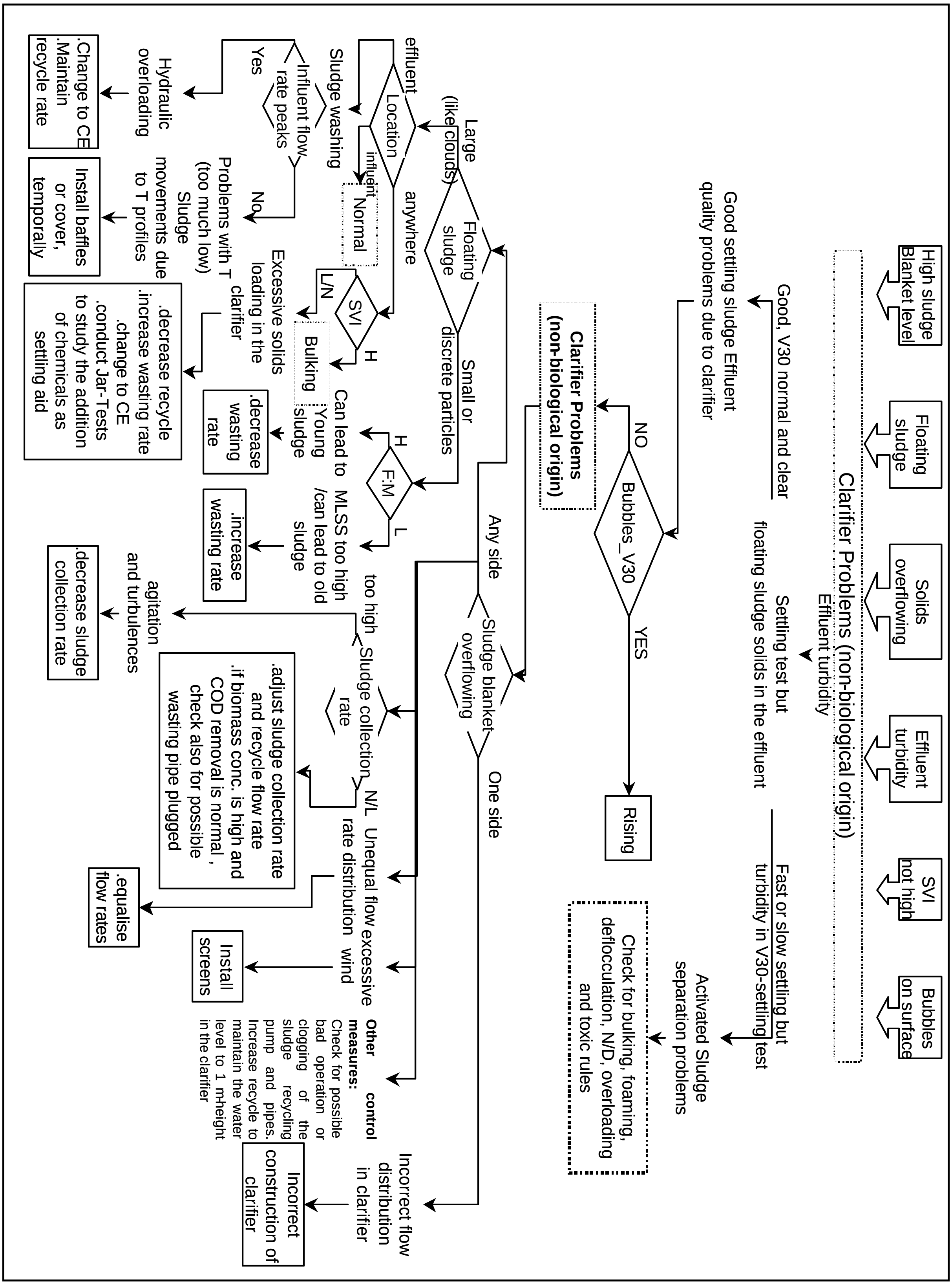
Fourth, if the wasting rate is not excessively high, then the secondary influent and return rates to each aeration tank are checked. If they are imbalanced, then this white foaming is caused by improper influent WW or RAS flow distribution causing overloading. The actuation is to modify distribution facilities as necessary to equalise influent wastewater and return rates to each aeration tank. MLSS, RAS and DO concentrations between the different tanks should be reasonably consistent.

Fifth and finally, if the secondary influent and RAS flow rates are balanced, then this white foam is produced by a young sludge in an overloaded aeration tank (low MLSS) (this is a typical problem during start-up and is only temporary. If starting up, do not worry about it.

In this case of overloading (MLSS too low), calculate the F/M ratio including BOD from any recycled in-plant side streams as digester supernatant or filtrate that are on line and the MLSS inventory. It should give a F/M high and a low MLSS. Therefore, the action plan consists in do not waste sludge from the process for a few days or maintain the minimum wasting rate possible to compensate for heavier loading. Increase return rate. If the activated sludge do no settle correct, add coagulant to enhance thickening in secondary clarifier. This situation can lead to dispersed-growth.

To detect the real cause, check for the DO level. If it is too high, than the cause is an excessive aeration (could conclude in a pin-point floc). The actuation consists in to maintain the DO level between 2 and 3 mg/l and to ensure an adequate mixing. After checking the DO level, If the secondary clarifier effluent presents solids carry-over and really looks cloudy, then the cause of reducing MLSS and increasing F/M (overloading) is a washing out process in the clarifier. The actuation consists in maintain sufficient return rates to minimise solids carry-over, especially during peak flow periods. A toxic waste recovery could also be the cause.

DECISION TREE CLARIFIER PROBLEMS (NON-BIOLOGICAL ORIGIN)



Clarifier Problems (non-biological origin)

This is a decision tree for detecting the non-biological underlying problems for cloudy secondary clarifier effluent. In this case, there is a large fan of possible causes responsible of the cloudy effluent.

Indicators/Symptoms

There are two clear conditions that indicate a possible non-biological problem of the secondary clarifier. These are a turbid secondary effluent but a good settleabilty (a normal or low SVI value and a clear supernatant in 30 min-test).

Diagnosis

Key variables : effluent turbidity, settleability (V30, 30 min-settling test supernatant), bubbles at the V30-settling test, sludge blanket over flowing, floating sludge.

The diagnosis process starts when the operator has introduced the results of his/her determinations into the system. In this case, starts checking the effluent turbidity. In case it is higher than the normal, then the activated sludge settleability is examined in the 30 minutes settling test. If these tests result in a high value of V30 or present turbidity in the supernatant, then the underlying problem is an activated sludge separation problem (a problem with biological origin, involving microorganisms anomalies). On the contrary, i.e., a low or normal value of V30 and a clear supernatant in the settling test indicates clarifier problems of non-biological origin, if previously denitrification in secondary settler (rising) has been rejected. This decision is made inspecting the presence of bubbles in the settling test. If rising is inferred, rising rules are invoked.

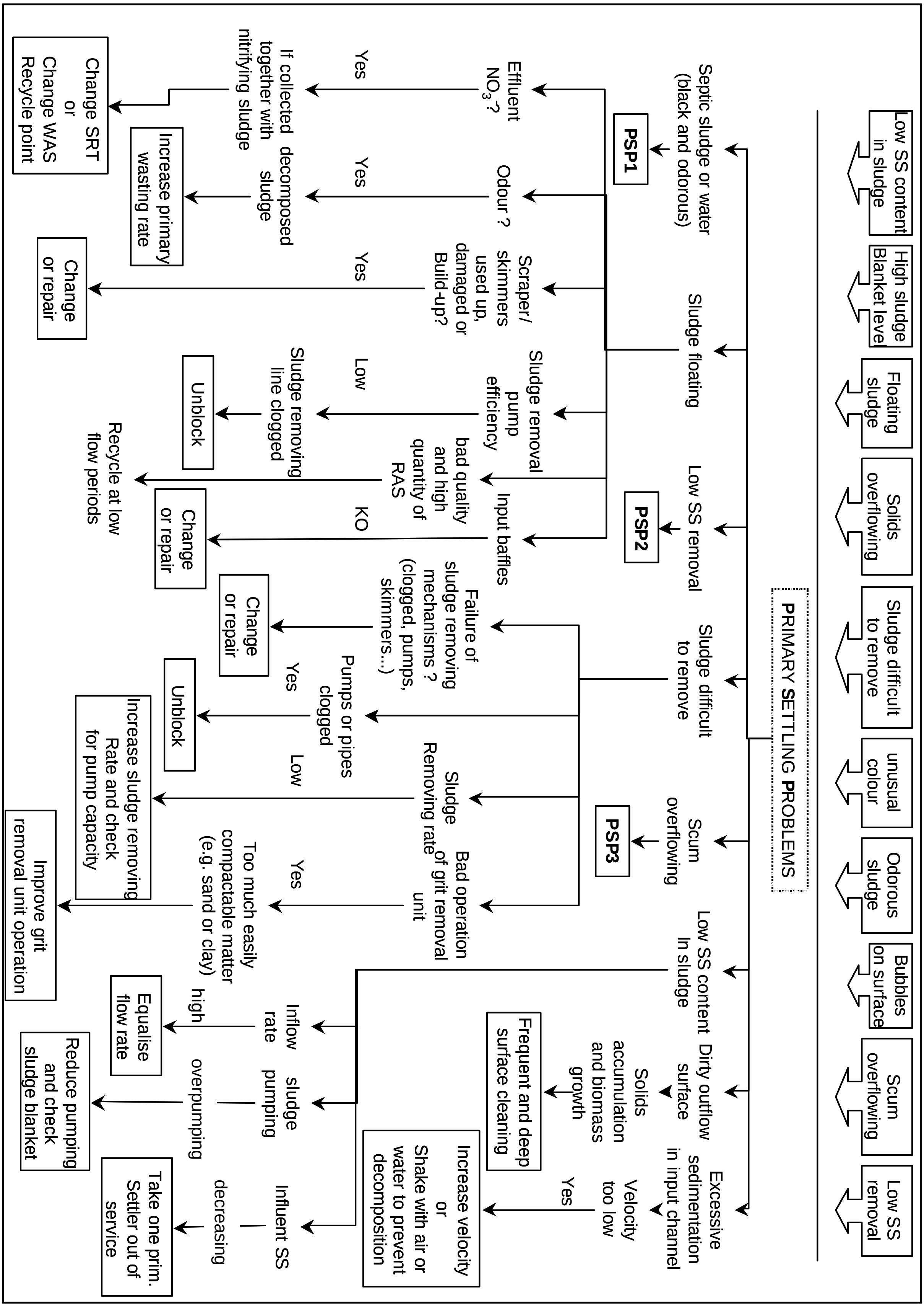
If the non-biological problems of secondary settler are certified, then the position of sludge blanket overflowing is checked. If sludge blanket overflows in only one area of secondary clarifier, then the cause is an unequal flow distribution within the clarifier. Probably the clarifier was bad designed and built. Action plans must check for effluent weir level.

If sludge blanket uniformly overflows in secondary clarifiers, the causes can be diverse. The first variable checked for cause identification is the presence of floating sludge. If floating sludge particles are small or discrete, the system must check for possible improper loading ratios. On the contrary, if sludge floating particles are large and located to anywhere in the clarifier, the cause of problem inferred will be an excessive solids loading rate, previous rejection of bulking. If the particles are large but located in the effluent, the clarifier problems are assigned to hydraulic overloading (hydraulic shocks) or problems with temperature profiles, according to whether influent peak flows are presented or not.

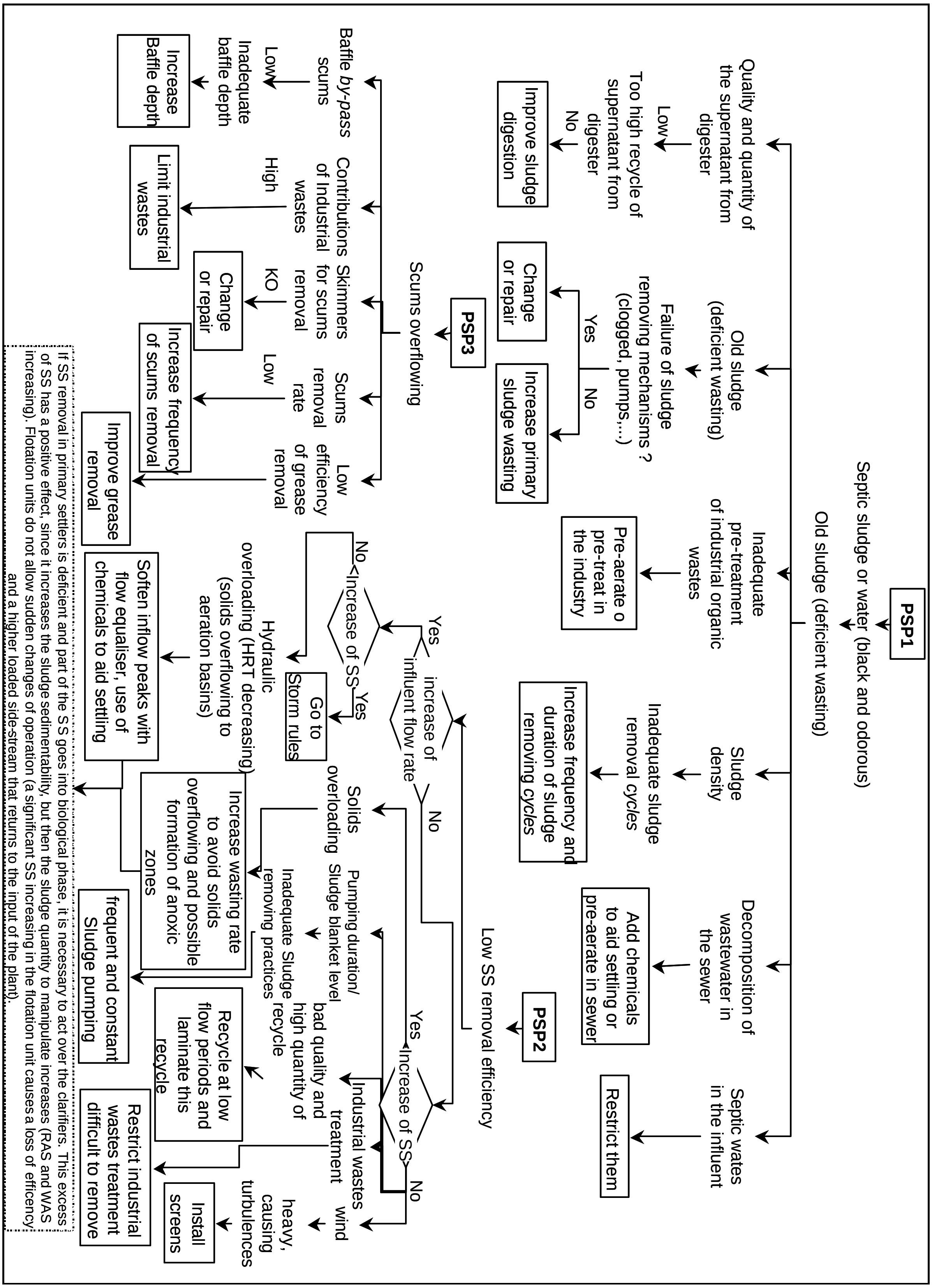
Secondly, an abnormal value of the sludge collection rate is checked (too high or low wasting and/or recycle flow rate). If it is unusual, adjust sludge collection rate and increase sludge return flow rate and monitor sludge blanket (maintain to 30 to 90 cm.). If biomass concentration is high and COD removal is normal, check also for possible wasting pipe plugged. Check also for septic sludge or anaerobic conditions due to insufficient sludge removing or recycling.
The other possible causes of clarifier problems (with non-biological origin) are next mentioned with the corresponding actuation to be applied :

Cause	Actuation
Hydraulic overload to a clarifier due to an unequal flow distribution (flow imbalance)	Adjust flow control devices (valves and weirs) to equalise flow to aeration tanks and clarifiers
Excessive wind around clarifier	Provide wind screen if clarifier is large
Sludge flowing for temperature currents by taking clarifier temperature profiles (colder water) (if deeper T is cooler by 2-4 F, T currents are present)	Install baffles If currents caused by solar surface warming, take a clarifier off-line or cover temporarily, if possible
Other control measures : Check for equipment malfunctions (flow meters for calibration, the possible bad functioning or plugging of recycle and wasting sludge pumps and pipes, sludge collectors for damage, clarifier inlet and outlet baffles for damage, weirs for level) and repair or replace this equipment. Increase recycle sludge rate to maintain 1 meter of clear water in the clarifier. Conduct settling aid jar tests to improve solids capture.	

DECISION TREE FOR PRIMARY TREATMENT PROBLEMS



DECISION TREE FOR PRIMARY TREATMENT PROBLEMS (cont.)



Primary Treatment Problems

This is a decision tree for detecting the primary treatment problems. In this case, there is a large fan of possible causes responsible of the malfunctioning of primary clarifier.

Indicators/Symptoms

There is a set of observations indicating primary sedimentation problems. These are: Floating sludge, black and odorous septic wastewater or sludge, scum overflow, sludge hard to remove from hopper, undesirable low solids contents in sludge, solids overflowing, bubbles on primary settler surface and high sludge blanket level, poor suspended solid removal, excessive biomass growth on surfaces and weirs.

Diagnosis

Key variables: septic wastewater or sludge, sludge floating, SS removal efficiency, primary wasting rates insufficient, scum overflowing, dirty output surface (excessive biomass growth on surfaces and weirs), velocity of primary settler, too low suspended solids content in sludge.

The diagnosis process starts when the operator has introduced the results of his/her determinations into the system.

Causes and actuations

The ES starts checking for a septic wastewater or sludge. If there is encountered a black and odorous septic wastewater or sludge, then the expert system looks for the possible different causes. Each cause will be identified by a distinguishing remark. Each remark, cause and related actuation to black and odorous septic wastewater or sludge (old sludge) are showed in the next table:

Remark	Cause	Actuation
Low quality and high quantity of digester supernatant	Recycle of excessively strong digester supernatant	Improve sludge digestion to obtain better quality supernatant. Provide treatment before recycle. Recycle at periods of low flow. Reduce or delay withdrawal until quality improves. Select better quality supernatant from another digester zone. Discharge supernatant to lagoon, aeration tank or sludge-drying bed.
Sludge removal mechanisms damaged	Sludge collectors worn or damaged Sludge withdrawal line plugged	Repair or replace as necessary Clean line
Bad pre-treatment practices (septic sewage from collection systems)	Inadequate pre-treatment of organic industrial wastes	Pre-aerate waste, add an oxidant to collection system (usually chlorine), reduce detention time in collection system and pre-treatment at the industry
High sludge density	Improper sludge removal pumping cycles Insufficient run time for sludge collectors	Increase frequency and duration of pumping cycles until sludge density decreases Increase run time or run continuously
Too high retention time and slow velocity in collection lines	Wastewater decomposing in collection system	Add chemicals or aerate in collector system
Random sampling of trucks	Septic wastes in the effluent	Regulate or curtail dumping

After exploring for septic water, the next observation is the presence or not of sludge floating. Each different remark, cause and actuation that an concludes to sludge floating are mentioned in the next table:

Remark	Cause	Actuation
High nitrate effluent	Return of well-nitrified waste activated sludge	Vary age of returned sludge or recycle waste sludge to an alternate process
Septic odour	Excessive sludge accumulating in the tank	Remove sludge more frequently or at a higher rate
Damaged or used-up collection equipment Skimmings build-up	Damaged or worn collection equipment (scrapers worn or damaged) Skimming collection system malfunction Skimming not removed often enough	Repair or replace as necessary Check skimming operation and correct if necessary Operate skimmer more often
Bad quality or high quantity of recycled waste sludge	Bad quality or high quantity of recycled waste sludge	Recycle at periods of low flow or recycle to different treatment process
Sludge removal pump efficiency Sludge washout from tank	Sludge withdrawal line plugged Pump cycling (surging flow)	Flush or clean line Modify pumping strategies. Increase tank volume or use an equalisation basin

Damaged input baffles	Damaged or missing inlet baffles	Repair, replace or install baffles

If there is no floating sludge, the system explores whether the SS removal efficiency is low or not. If it is low, we can distinguish different possible causes. First, the system checks for an increasing in water inflow and influent suspended solids. Four possible situations are presented: (i) if the inflow and the influent SS has increased, then an storm situation is detected and the associated actuation is proposed; (ii) if the inflow has increased but the influent SS has not, then a hydraulic overloading (decreasing in detention time) is detected with solids overflowing to the aeration basins. The actuation proposed is to use all available tanks, to shave peak flows with flow equaliser (to increase detention time) or consider chemical coagulants addition; (iii), if the influent SS has increased but the water inflow has not, then a solids overloading is detected and the actuation consists in increasing primary waste sludge to avoid solids overflowing and formation of anoxic zones; and (iv) finally, if neither the influent flow rate nor the influent SS have increased, other possible causes and the associated actuation concluding to low SS removal efficiency are explored in the next table:

Remark	**Cause**	**Actuation**
Low pumping duration Too high sludge blanket	Inadequate sludge removal practices	Establish a more frequent and constant pumping schedule
Bad quality and high quantity of recycles	Recycle strongly loaded	Recycle at low flow periods or re-route recycle flows to an alternate process Lamination of this high loaded recycles
Influent industrial waste	Industrial waste treatment	Identify and restrict or eliminate any industrial waste that may hinder settling
pH, DO, H_2S	Septic influent	Intensify and resolve upstream causes. Pre-treat with chlorine or other oxidizing chemical until problem is resolved
Wastewater temperature and winds	Density currents wind or temperature related	Eliminate storm flows for sewer system. Install wind barriers.

If the SS removal efficiency is not low, then the system explores for a low primary wasting sludge rates. The remarks of each cause, the causes themselves and the corresponding actuation are presented in he next table:

Remark	**Cause**	**Actuation**
Pipe or pump clogged		Unblock clogged pipe lines and pump sludge more frequently
Low primary sludge removal velocity	Low velocity in withdrawal lines	Increase velocity in withdrawal lines. Check pumps capacity.
Velocity too low, high blanket levels	Sludge settling in influent lines	Agitate with air or water to keep the material suspended until it reaches the tank Increase operation of collection equipment and primary sludge pumping rate
Deficient purge		Increase primary sludge wasting rates
Bad operation of grit removal	Excessive grit, clay and other easily compacted material	Improve operation of grit removal unit
Sludge removal mechanisms damaged	Sludge collectors worn or damaged Sludge withdrawal line plugged	Repair or replace as necessary Clean line
Skimmers not skimming properly	Flight or blade height not properly set Beach not properly adjusted (circular tank)	Adjust to proper setting Adjust height

After checking for the wasting rates, a possible scum overflowing is checked. If the scum overflows through the primary clarifier, different possible causes are considered. They are resumed in the next table:

Remark	**Cause**	**Actuation**
Scum bypassing baffle	Inadequate depth of scum baffle	Increase baffle depth
Influent industrial waste detected	Heavy industrial waste contributions	Identify and restrict industrial waste contributions
Skimmers damaged	Worn or damaged skimmers	Clean or replace skimmers
Skimmings build-up	Skimming collection system malfunction Skimming not removed often enough	Check skimming operation and correct if necessary. Operate skimmer more often
Low scum removal velocity	Inadequate scum removal frequency	Remove scum more frequently
Foaming	A foaming substance has entered the plant	Identify and restrict this possible industrial contribution Use spray water or foam reducing chemicals to keep foam down
Bad operation of grit chamber	-	Improve grit chamber (greases and fats removal) operation

Industrial contributions	Unusual amount of floatable material	Operate skimmer as often as possible. Remove manually, if necessary

After checking for scum overflowing, the expert system looks for dirty surfaces. If accumulations of wastewater solids and resultant growth or debris are observed on surfaces and weirs (dirty outflow surfaces), then a more frequent and thorough cleaning of surfaces is needed. Late, the system explores for the velocity of the primary settler. If there is an excessive sedimentation in inlet channel, then the actuation should be an increase in the velocity or agitate with air or water to prevent de-composition.

Finally, the system explores for too low SS contents in sludge. The different possible causes and actuations are summarised in the next table:

Remark	**Cause**	**Actuation**
High influent flow rate	Hydraulic overloading	Provide more even flow distribution in all tanks
Bad frequency and duration of sludge pumping	Overpumping of sludge	Reduce frequency and duration of pumping cycles. Check blanket levels
Decreased influent SS	Influent SS loading	Take one or more primary tanks out of service