Universitat de Girona

# DEVELOPMENT OF AN ENVIRONMENTAL DECISION SUPPORT SYSTEM FOR THE SELECTION AND INTEGRATED ASSESSMENT OF PROCESS FLOW DIAGRAMS IN WASTEWATER TREATMENT

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*PhD Thesis*

# Development of an environmental decision support system for the selection and integrated assessment of process flow diagrams in wastewater treatment

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**Certifiquen**

Que el llicenciat en Ciències Ambientals Manel Garrido Baserba ha realitzat, sota la seva direcció, el treball que amb el títol "Development of an environmental decision support system for the selection and integrated assessment of process flow diagrams in wastewater treatment", es presenta en aquesta memòria la qual constitueix la seva Tesi per optar al Grau de Doctor per la Universitat de Girona.

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

Girona, Gener de 2013

Manel Poch Espallargas

Luis Larrea Urcola

**Als meus,**

***Mama, papa, cris i avis***

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# SUMMARY

Wastewater treatment has become an important environmental issue because it plays a fundamental role in keeping natural water resources at as high quality as possible. Whatever the technology and the treatment level required, WWTPs are considered complex systems (1.1 Wastewater Treatment Plants (WWTPs)) and all decisions related within this field are sensitive to this inherent complexity (1.2 Decision in WWTPs). In this respect, Environmental Decision Support Systems (EDSSs) have generated high expectations as tools to handle properly the complexity associated with the WWTP management. An EDSS can be defined as interactive, flexible and adaptable software, which links numerical models/algorithms with knowledge- based techniques, geographical information and environmental ontologies, and are developed to support environmental decision-makers (1.3. Supporting the decision-making process) in choosing between alternatives by improving their decisions-making process and providing the proper integrated assessment of the alternatives options (1.4 Integrated assessment in WWTPs).

The present thesis has been developed within a project framework which aims to build an EDSS to support the selection and integrated assessment of any kind of WWTP depending the wide range of the current and possible existing scenarios (2. Objectives).

The first step to achieve our purpose was the selection of a methodology to develop the NOVEDAR_EDSS. In this respect, we choose the five-step methodology proposed by Poch et al. (2004) because (1) it was successfully applied in the construction of more than ten EDSSs in the water management framework and (2) it provides a certain flexibility to acquire and integrate data and knowledge required to solve water environmental problems (3. Building the NOVEDAR_EDSS).

The development of the NOVEDAR_EDSS started with the analysis of the wastewater management problem (3.1. Environmental problem analysis). A wide research enabled to carry out a detailed study about the complexity associated to the conceptual design of WWTPs (3.2. Data collection and knowledge acquisition). This domain analysis permitted to define the requirements to develop the NOVEDAR_EDSS. All these data and knowledge was analyzed, categorized, and properly organized according our EDSS structure and system capabilities (3.3. Data and knowledge analysis). Next step in the development of the NOVEDAR_EDSS was the selection of a methodology to handle and represent the acquired data and knowledge (3.4. Model selection). After a thoroughly analysis, and the consideration of the available methods, we choose a Knowledge-based System. Following all steps required for the implementation of this system and other complementary methodologies is detailed (3.5. Model implementation and integration). In the last step, the validation procedure of the system is detailed. (3.6. Evaluation and validation).

The operation of the developed NOVEDAR_EDSS is also illustrated. The operation chapter intends to become a useful guide to provide the elementary information about the “how to operate” the NOVEDAR_EDSS and to maximize the potentialities of the EDSS. This kind of user guide goes through all

the software sections, procedure steps and extra capabilities included in the EDSS (4.Operation of the NOVEDAR_EDSS).

An important step to confirm the capabilities and explore the NOVEDAR_EDSS potential is the evaluation and validation process which aims to verify with real studies whether we have built the system “right” and whether we have built the “right” system. To confirm the efficacy and suitability of the EDSS three publications are presented to evidence the potential and validity of the EDSS. The three examples considered as validation proofs of the reliability of the EDSS have been accepted or submitted in scientific journals. Each of them is mainly focused in the main topics within the EDSS scope: i) Environmental (5. Including the environmental vector when selecting a wastewater treatment plant); ii) Economic (6. Assessment of wastewater treatment plants design for small populations: technical and economic aspects.); and iii) Technical (7. IEDSS as a Tool for the Integrated Assessment of Conventional and Innovative Wastewater Treatment Technologies for Nutrient Removal).

Finally, the main conclusions derived from this thesis are enumerated and some challenges to be solved in a near future are presented in chapter 8 (8. Conclusions).

# RESUM

El tractament de les aigües residuals s'ha convertit en una prioritat i juga un paper fonamental en el manteniment dels recursos hídrics naturals. Sigui quin sigui el conjunt de tecnologies de tractament emprades o el nivell de depuració requerit, qualsevol planta de tractament d'aigües residuals ha de ser considerada com un sistema o conjunt de processos lligats a una elevada complexitat (1.1 Plantes de Tractament d'Aigües Residuals (EDAR)) i on totes les decisions relacionades dins d'aquest àmbit són sempre sensibles a aquesta complexitat inherent (1.2 Decisions a les EDAR). En aquest sentit els sistemes de Suport a la Decisió en dominis ambientals (EDSSs, per les sigles en anglès) han generat grans expectatives com a eines per gestionar adequadament la complexitat associada al tractament d'aigües residuals. Un EDSS pot definir-se com un programari interactiu, flexible i adaptable, que vincula els models numèrics / algoritmes amb tècniques basades en el coneixement, la informació geogràfica i ontologies ambientals, i que s'han desenvolupat per donar suport a tots aquells responsables de la presa de decisió dins de qualsevol projecte, (1.3. Suport durant el procés de presa de decisió) ja sigui en l'elecció entre les diferents alternatives, millorant les opcions o solucions al problema, o bé, en la correcta avaluació integrada de les diferents opcions (1.4 Avaluació integrada de les EDAR).

Aquesta tesi s'ha desenvolupat dins del marc d'un projecte que té com a objectiu integrar el màxim de coneixement científic amb relació el tractament d'aigües residuals i construir un EDSS per donar suport a la selecció i l'avaluació de configuracions d'EDAR en funció de l'àmplia gamma de possibles escenaris existents avui dia (2. Objectius).

El primer pas per aconseguir el nostre propòsit ha estat la selecció d'una metodologia per desenvolupar el anomenat NOVEDAR_EDSS. En aquest sentit, s'escull la metodologia de cinc passos proposada per Poch et al. (2004) ja que (1) es va aplicar amb èxit en la construcció de més de deu EDSSs en el marc de la gestió de l'aigua i (2) que proporciona una certa flexibilitat per adquirir i integrar les dades i els coneixements necessaris per resoldre els problemes ambientals lligats a l'aigua.

El desenvolupament del NOVEDAR_EDSS (3. Construint el NOVEDAR_EDSS) comença amb l'anàlisi del problema que volem abordar en relació a les opcions de tractament de les aigües residuals (3.1. Anàlisi del probleme ambiental). Una àmplia recerca va permetre dur a terme un estudi detallat sobre la complexitat associada al disseny conceptual de les EDAR (3.2. Recollida de dades i adquisició del coneixement). Aquesta anàlisi del domini ambiental va permetre definir els requisits necessaris per desenvolupar el NOVEDAR_EDSS. Totes aquestes dades i coneixements es va analitzar, classificar i degudament organitzar segons l'estructura i les capacitats del sistema que es requeria (3.3. Anàlisi de les dades i del coneixement). El següent pas en el desenvolupament del NOVEDAR_EDSS va ser la selecció d'una metodologia capaç de gestionar i representar les dades i coneixements adquirits (3.4. Selecció del model). Després d'una anàlisi a fons, i la consideració de tots els mètodes disponibles, es va triar un sistema basat en la gestió del coneixement. A continuació es proporcionen els detalls i tots els passos necessaris per a la implementació d'aquest sistema i de la resta de metodologies complementàries

aplicades al EDSSs (3.5. Implementació dels models i integració). En l'últim pas, el procediment utilitzat per validar el sistema es troba detallat (3.6. Avaluació i validació).

El funcionament a nivell d'usuari del NOVEDAR_EDSS també s'explica en detall en el capítol d'operació. Així, doncs, el capítol d'operació del EDSS pretén esdevenir una mena de guia per proporcionar la informació bàsica sobre el "com" funciona i s'opera el NOVEDAR_EDSS, i com aprofitar al màxim les potencialitats que ofereix el sistema de suport. Aquesta mena de manual repassa totes les seccions de programari, passos durant el procés de presa de decisió i totes les capacitats addicionals incloses en el EDSS (4.Operation del NOVEDAR_EDSS).

Un pas important per confirmar les capacitats de suport i explorar el vertader potencial del NOVEDAR_EDSS és el procés d'avaluació i validació del EDSS. Amb aquesta intenció es presenten com a proves per confirmar l'eficàcia i la idoneïtat del EDSS tres publicacions científiques. Les publicacions considerades com a proves de validació i que demostren de la fiabilitat dels EDSS han estat admeses i presentades en revistes científiques dins del àmbit en qüestió. Cada una d'elles es centra principalment en algun dels temes principals del camp del EDSS: i) medi ambient (5 Inclusió del vector ambiental quan es selecciona una planta de tractament d'aigües residuals), ii) Econòmic (6 Avaluació de les plantes de tractament d'aigües residuals per a poblacions petites disseny:. Tècnica. i els aspectes econòmics.), iii) Tècnics (7 IEDSS com a eina per a l'avaluació integrada de tecnologies de tractament d'aigües residuals convencionals i innovadores per a l'eliminació de nutrients).

Finalment, les principals conclusions derivades d'aquesta tesi s'enumeren , es discuteixen, i es presenten en el capítol 8 juntament amb alguns dels reptes que cal resoldre en un futur pròxim (8. Conclusions).

# RESUMEN

El tratamiento de las aguas residuales se ha convertido en una prioridad y juega un papel fundamental en el mantenimiento de los recursos hídricos naturales. Sea cual sea el conjunto de tecnologías de tratamiento empleadas o el nivel de depuración requerido, cualquier planta de tratamiento de aguas residuales debe ser considerada como un sistema o conjunto de procesos ligados a una elevada complejidad (1.1 Plantas de Tratamiento de Aguas Residuales (EDAR)) y donde todas las decisiones relacionadas en este ámbito son siempre sensibles a esta complejidad inherente (1.2 Decisiones en las EDAR). En este sentido los sistemas de Apoyo a la Decisión en dominios ambientales (EDSS, por sus siglas en inglés) han generado grandes expectativas como herramientas para gestionar adecuadamente la complejidad asociada al tratamiento de aguas residuales. Un EDSS puede definirse como un software interactivo, flexible y adaptable, que vincula los modelos numéricos / algoritmos con técnicas basadas en el conocimiento que se han desarrollado para apoyar a todos aquellos responsables de la toma de decisión dentro de cualquier proyecto, (1.3. Apoyo durante el proceso de toma de decisión) ya sea en la elección entre las diferentes alternativas, mejorando las opciones o soluciones al problema, o bien, en la correcta evaluación integrada de las diferentes opciones (1.4 Evaluación integrada en las EDAR).

Esta tesis se ha desarrollado en el marco de un proyecto que tiene como objetivo integrar el máximo de conocimiento científico con relación al tratamiento de aguas residuales y construir un EDSS para apoyar a la selección y evaluación de configuraciones de EDAR en función de la amplia gama existente hoy día de posibles escenarios (2. Objetivos).

El primer paso para conseguir nuestro propósito ha sido la selección de una metodología para desarrollar el llamado NOVEDAR_EDSS. En este sentido, se escoge la metodología de cinco pasos propuesta por Poch et al. (2004) ya que (1) se aplicó con éxito en la construcción de más de diez EDSS en el marco de la gestión del agua y (2) que proporciona una cierta flexibilidad para adquirir e integrar los datos y los conocimientos necesarios para resolver los problemas ambientales ligados al agua.

El desarrollo del NOVEDAR_EDSS (3. Construyendo el NOVEDAR_EDSS) comienza con el análisis del problema que queremos abordar en relación a las opciones de tratamiento de las aguas residuales (3.1. Análisis del problema ambiental). Una amplia investigación permitió estudiar en detalle la complejidad asociada al diseño conceptual de las EDAR (3.2. Recogida de datos y adquisición del conocimiento). Este análisis del dominio ambiental permitió definir los requisitos necesarios para desarrollar el NOVEDAR_EDSS. Todos estos datos y conocimientos se analizaron, clasificaron y fueron debidamente organizados según la estructura y las capacidades del sistema que se requería (3.3. Análisis de los datos y del conocimiento). El siguiente paso en el desarrollo del NOVEDAR_EDSS fue la selección de una metodología capaz de gestionar y representar los datos y conocimientos adquiridos (3.4. Selección del modelo). Tras un análisis a fondo, y la consideración de todos los métodos disponibles, se eligió un sistema basado en la gestión del conocimiento. Seguidamente se proporcionan los detalles y todos los pasos necesarios para la implementación de este sistema y del resto de metodologías complementarias

que fueron aplicadas al EDSS (3.5. Implementación de los modelos y integración). En el último paso, se encuentra el procedimiento utilizado para la validación del sistema (3.6. Evaluación y validación).

El funcionamiento a nivel de usuario del NOVEDAR_EDSS también se explica en detalle en el capítulo de operación. Así pues, el capítulo de operación del EDSS pretende convertirse en una especie de guía para el usuario que permita proporcionar la información básica sobre el "cómo" funciona y “cómo” se opera el NOVEDAR_EDSS. Este tipo de manual repasa todas las secciones de software, pasos durante el proceso de toma de decisión y todas las capacidades adicionales incluidas en el EDSS (4.Operation del NOVEDAR_EDSS).

Un paso importante para confirmar las capacidades de soporte y explorar el verdadero potencial del NOVEDAR_EDSS es el del proceso de evaluación y validación del EDSS. Se presentan como pruebas para confirmar la eficacia y la idoneidad del EDSS tres publicaciones científicas. Las publicaciones que demuestran la fiabilidad de los EDSS han sido admitidas y presentadas en revistas. Cada una de ellas se centra principalmente en alguna de las temáticas principales del EDSS: i) medio ambiental (5 Inclusión del vector ambiental cuando se selecciona una planta de tratamiento de aguas residuales), ii) económica (6 Evaluación de las plantas de tratamiento de aguas residuales para poblaciones pequeñas diseño: Técnica. y los aspectos económicos.), y iii) Técnica (7 IEDSS como herramienta para la evaluación integrada de tecnologías de tratamiento de aguas residuales convencionales e innovadoras para la eliminación de nutrientes).

Finalmente, las principales conclusiones derivadas de esta tesis se enumeran, se discuten y se presentan en el capítulo 8 junto con algunos de los retos que hay que resolver en un futuro próximo (8. Conclusiones).

## PREFACE

The Laboratory of Chemical and Environmental Engineering (LEQUIA, from Laboratory d'Enginyeria Quimica i Ambiental, in Catalan) of the University of Girona (UdG, from Universitat de Girona) started the research around the application of Environmental Decision Support Systems (EDSSs) in 1990. The LEQUIA research group participated actively in the creation and configuration of the NOVEDAR_Consolider network under the project "Conception of the WWTP of the XXI century”. This Project has been financed by the Spanish Ministry of Education and Science (Consolider Project-NOVEDAR) (CSD2007-00055). This institution together with 8 Spanish and 2 Dutch groups integrates the consortium born on the 2007. Each of the groups has a particular expertise, and complementarity between research centers was of the upmost importance. The expertise in designing real EDSS of the LEQUIA groups led to the development of the NOVEDAR_DSS. Most of the PhD work of the candidate Manel Garrido Baserba has been framed within the NOVEDAR_Consolider project.

http://www.novedar.com

http://lequia.udg.es/

The Catalan Institute for Water Research (ICRA) was created on 26 October 2006 by the Government of Catalonia within the framework of the Research Centres Programme of Catalonia (CERCA). It is an international reference point in the research of the integral water cycle, hydraulic resources, water quality (in the broadest sense of the term: chemical, microbiological, ecological, etc.) and treatment and evaluation technologies. This research Centre supported the project NOVEDAR_Consolider during almost all the thesis period (June 2008-2012). H2O Building has been funded by the Ministry of Economy and Competitiveness (MINECO) and European Regional Development Fund (ERDF) under the ERDF Operational Programme 2007-2013 in Catalonia.

http://www.icra.cat/index.php

## *List of Publications*

**The research work carried out within this project has enabled to produce several communications and publications. Most of the work presented in international conferences and/or in journal publications is compiled within the PhD document while others have become the groundwork needed to develop the thesis. The following list contains the publications of the PhD candidate together with his contributions in each paper:**

**M. Garrido-Baserba**, R. Reif, F. Hernández and M. Poch (2012). *A novel knowledge-based methodology for generating suitable WWTP process flow diagrams*. Journal of Environmental Management. 112. 384-391

***Author's contribution:*** All the design, experimental study, data analysis, results discussion and developing the EDSS. Writing the paper, with contributions from the other authors.

**M. Garrido-Baserba**, R. Reif, I. Rodriguez-Roda and M. Poch (2011). *A knowledge management methodology for the integrated assessment of WWTP configurations during conceptual design*. Water Science and Technology 66 (1), 165-172

***Author's contribution:*** All the design, experimental study, data analysis, results discussion and developing the EDSS. Writing the paper, with contributions from the other authors.

M. Molinos-Senante, **M. Garrido-Baserba**, R. Reif, F. Hernández-Sancho and M. Poch (2012). *Assessment of wastewater treatment plants design for small communities: Environmental and economic aspects*. Science of theTotal Environment. 427-428, 11-18.

***Author's contribution:*** All the experimental study, data analysis and discussion, also the design of the economic module in the EDSS. Writing the paper, with contributions from the other authors.

**M. Garrido-Baserba**, A. Hospido, M. T. Moreira, R. Reif, G. Feijoo and M. Poch (2012). *Including the environmental vector when selecting a wastewater treatment plant*. Submitted to Environmental Modelling and Software.

***Author's contribution:*** All the experimental study and data analysis and discussion, and the implementation and design of the environmental module. Writing the paper, with contributions from the other authors.

**M. Garrido-Baserba,** R. Reif, L. Larrea and M. Poch (2012). *New Tool for the Integrated Assessment and Selection of Innovative Wastewater Treatment Technologies for Nutrient Removal.* Submitted to Environmental Science and Technology.

***Author's contribution:*** All the decision tree development, implementation, and data analysis and discussion of the results. Writing the paper, with contributions from the other authors.

**Additional relevant scientific contributions related to this thesis**

M. Molinos-Senante, F. Hernández-Sancho, R.Sala-Garrido and **M. Garrido-Baserba** (2010). Feasibility Study for Phosphorus Recovery Processes: an Economic Approach. AMBIO 40 (4), 408-416.

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**M.Garrido**, I. Rodríguez-Roda, X. Flores, M. Poch*. Development of a DSS for the generation of WWTP configurations alternatives.* In proceddings of the International Congress of Environmental Modeling and Software (EMSS2010) - Intelligent Environmental Decision Support Systems. Ottawa, Canadá. 2010

**M.Garrido**, X. Flores, M. Poch. *A Decision Support System to Face New Challenges in the Selection of WWTP Alternatives.* Oral contribution. In proceddings of IWA Specialist Conference "Water and Wastewater Treatment Plants in Towns and Communities of the XXI Century: Technologies, Design and Operation". Moscow, Russia. 2010

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**M.Garrido**, I. Rodríguez-Roda, M. Poch. *Development of the NOVEDAR_ DSS for the selection and integrated assessment of WWTPs alternatives.* Oral contribution at Water & Industry of the IWA specialist International Conference. NOVEDAR workshop. Valladolid, Spain. 2011

**M.Garrido**, A. Hospido, R. Reif, M. T. Moreira, G. Feijoo, M. Poch. *An innovative tool for wastewater treatment alternatives selection integrating knowledge-based methodologies and life cycle* *assessment*. Poster contribution of the IWA 9th Leading-Edge Conference on Water and Wastewater Technologies (LET2012). Brisbane, Australia. 2012.

M. Molinos-Senante, **M.Garrido**, R. Reif, F. Hernandez, M. Poch. *Decision Support System to Select WWTPs Technologies for Small Populations: Environmental and Economic Assessment*. Proceedings of the EcoSTP. Specialised IWA Conference on Ecotechnologies for Wastewater Treatment. Technical, Environmental and Economic Challenges (EcoSTP). Santiago de Compostela, Spain. 2012

R. Reif, **M.Garrido**, M. Poch. *IEDSS as a Tool for the Integrated Assessment of Conventional and Innovative Wastewater Treatment Technologies for Nutrient Removal.* Proceedings of the International Congress of Environmental Modeling and Software (EMSS2010) - Intelligent Environmental Decision Support Systems. Leipzig, Germany. 2012.

**M.Garrido**, J.Comas, M. Poch. *Multi-criteria decision support system for WWTP*. AtWAT. Specialised Workshop in Advanced Tools for Wastewater Treatment. Tiruchirappalli, India. 2013

**M. Garrido** and M. Poch (2011). Environmental Decision Support Systems (EDSSs). A tool for the wastewater management in the XXI century. NOVEDAR Books Vol. 8th.  Edition for the 4th NOVEDAR_Consolider Summerschool. Palahí Arts gràfiques, Girona

**M. Garrido**, R. Reif M. S. Morena, J. Comas, M. Poch (2012). Decisions and integrated assessment in WWTP management: NOVEDAR_EDSS. Vol. 1st. Edition for the ISSE 2012 "LCA and water issues" organised by LEQUIA-UdG.

Nowadays a paper which summarizes the capabilities implemented into the EDSS to support the selection of WWTPs according the new paradigms on the wastewater treatment is in preparation for the Water Research journal.

Besides, Manel Garrido Baserba is co-editor of the book edited for the 4th NOVEDAR_Consolider Summer School, in accordance with the collection of NOVEDAR Books. Also he was the responsible coordinator and technical secretary of the corresponding 4$^{th}$ Summer school held in Girona (July 2011).

The training of Manel Garrido Baserba has been complemented with six research stays carried out during his PhD student period. The first one was a short stage of one week at Centro de Estudios y Investigación Técnicas de Guipuzcoa (CEIT). In this stay the bases for the supervision, thesis monitoring and work programme with his Thesis Co-director Dr. Luis Larrea were established. While the other two short stages of one week were done at the Novedar centers to collect the required knowledge and to explain the EDSS aims and building planning. Stays were held at the University of València (UV) and Universidad de Cádiz (UCA). The other two were a 5-month stay at the Universidad de Santiago de Compostela (USC) under the supervision of Professors Almudena Hospido and Maite Moireira (5 October 20011– 10 March 2012) for the implementation and validation of a LCA methodology into the NOVEDAR_DSS; And a 3-month stay at Australian National University (ANU), in Canberra (Australia) under the supervision of Professor Anthony Jakeman (20 March – 20 June 20012) working on how to improve scientific communications of multi-objective and tradeoff problems in water management.

# Index of figures

# LIST OF ACRONYMS AND ABBREVIATIONS

AI: Artificial Intelligence

ANP: Analytical Network Process

AS: Activated Sludge

BAT: Best Available Technologies

BOD: Biological Oxygen Demand

CBA: Cost-Benefit Analysis

COD: Chemical Oxygen Demand

DPM: Data Processing Module

EDSS: Environmental Decision Support System

KB: Knowledge Base

KBS: Knowledge-based system

LCA: Life Cycle Assessment (or Analysis)

MCDM: Multi-Criteria Decision Method

NPV: Net profit Value

PE: Population Equivalent

PFD: Process Flow Diagram

RAS: Return Activated Sludge

RE: Recursive Evaluation

RBS: Rule Base System

SRT: Solids Retention Time

SS: Suspended Solids

TN: Total Nitrogen

TP: Total Phosphorus

WSM: Weighted Sum Method

WWTP: Wastewater Treatment Plant

# *Table of contents*

# Chapter 1

## Introduction

**PhD THESIS**

**Part of this chapter has been published as:**

**M. Garrido** and M. Poch (2011). Environmental Decision Support Systems (EDSSs). A tool for the wastewater management in the XXI century. NOVEDAR Books Vol. 8th. Edition for the 4th NOVEDAR_Consolider Summerschool. Palahí Arts gràfiques, Girona

**M. Garrido**, R. Reif, S. Morera, J. Comas, M. Poch (2012). Decisions and integrated assessment in WWTP management: NOVEDAR_EDSS. Chapter 7. 1$^{st}$. Edition for the ISSE 2012 "LCA and water issues" organised by LEQUIA-UdG.

# 1. INTRODUCTION

Water is crucial for all aspects of life, the defining feature of our planet. There is always the same amount of water in our planet, and it is the same that sustained (and composed) all species that ever lived in the earth. Ninety seven and a half per cent of all water is found in the oceans, of the remaining freshwater only one per cent is accessible for extraction and use.

At the beginning of the 21st century, the world faces a water crisis. Environmental stresses imposed by population growth, urbanization, industrialization and climate change have become a prominent theme of international concern. One of the most affected natural resources is that of freshwater (IWMI, 2007). Demands upon the world's supply of freshwater resources are increasing the threats and risk to both the quantity and quality of a natural resource essential to human life, health, social and economic activities. This current impact in our environment has forced society to consider changes in human behavior to ensure the essential conditions for life on our planet (UN, 2005).

Wastewater – spent or used water from urban areas, villages, homes, farms or industry may contain harmful dissolved or suspended matter. Unregulated discharge of wastewater undermines biological diversity, natural resilience and the capacity of the planet to provide fundamental ecosystem services, impacting both rural and urban populations and affecting sectors from health to industry, agriculture, and tourism (UN, 2005). Therefore, the wastewater treatment has become one of the most important environmental issues because its treatment is fundamental to keep and increase the quality of the water natural resources.

The European Directive 91/271 establishes that every European city or village must treat its wastewater, at least, reducing to an specific concentration the Suspended Solids (SS), the Biological Oxygen Demand (BOD) and the Chemical Oxygen Demand (COD) contained in the wastewater. Thus, the correct selection and management of the facilities and technologies responsible for the wastewater treatment has become very important, not only because of more and more restrictive environmental regulations and social considerations but also for economic and technical reasons. The complexity associated with those facilities involved in the wastewater treatment plants (1.1. Wastewater treatment plants (WWTPs)) led to the need for new tools (1.3.1 Environmental decision support systems (EDSSs)). Although several attempts have been made to apply these new tools in WWTP management, few advances have been made in the conceptual design and WWTP configuration selection for specific scenarios following the XXI century wastewater treatment paradigm (1.4 WWTPs integrated assessment).

Therefore, a new approach to handle this issue is proposed (1.5 integrated assessment, WWTPs and EDSS: A new approach).

### 1.1. WASTEWATER TREATMENT PLANTS (WWTPS)

A WWTP can be defined as an industrial facility which receives wastewater (and sometimes runoff) from domestic and/or industrial sources, and through a combination of physical, chemical and biological processes reduces (treats) the wastewater to less harmful by-products. The interactions among physical, chemical and biological processes convert WWTPs to complex systems. The selection of the most suitable technologies for each case or scenario requires multi-disciplinary approaches and expertise from different social, technical and scientific fields (Flores-Alsina et al., 2010; Poch et al., 2004).

Therefore, the selection of the proper WWTP configuration should be respectful with the environment, economically affordable and, finally, must seek for social equity (personal and territorial), but not at any environmental impact and economic cost. So, there are frequently conflicting objectives. Since different partners with various interests, often contradictory are involved. Therefore, the concept of efficient management might be understood in a different way depending on the person who considers it. Decisions, which must be undertaken at different levels, involve different ways of managing this resource efficiently. However, there are no unique or global solutions, and the accumulated experience shows that some solutions are indeed better than others.

## 1.2. DECISIONS IN WWTPs

Almost all decisions in every decisive area of our society development, including the wastewater management have been ruled by costs and economic feasibility. The implementation of strict directives to protect water resources promoted the need to build at rapid pace facilities for the wastewater treatment and imposed economically sound approaches. Although those facilities were required in order to avoid our ecosystems degradation, these options may not be the most favorable in all the cases. Scientific approaches bring light to the direct consequences of this fact realizing how sustainability was usually kept away during this process. Thus, the consideration of only one dimension (economic) to assess processes or products/activities is no longer enough. For this reason, one of the main actions towards the reduction of environmental impacts and sustainability has to be focused in considering the wide range of implications from any selected option and not just choosing those solutions that only maximize short-term benefits.

However, a definite component must be considered when talking about proper solutions and decision-making: Time. Not every decision taken during a project has the same impact on the final result. The earlier the decisions are taken, the higher the benefits in our activities and projects. In this way, the time sequence of decisions taken during any wastewater project necessarily has to be considered. Every wastewater project begins with consideration of the broad range of wastewater management options, of which treatment facilities are only one component, and proceeds through the detailed development of specific treatment facilities. Therefore, the opportunities to reduce costs and enhance the value provided by the wastewater management option implemented decline as the project proceeds. So, the greatest opportunity exists when wastewater management options are being evaluated and are the lowest when the required facilities are detailed design.

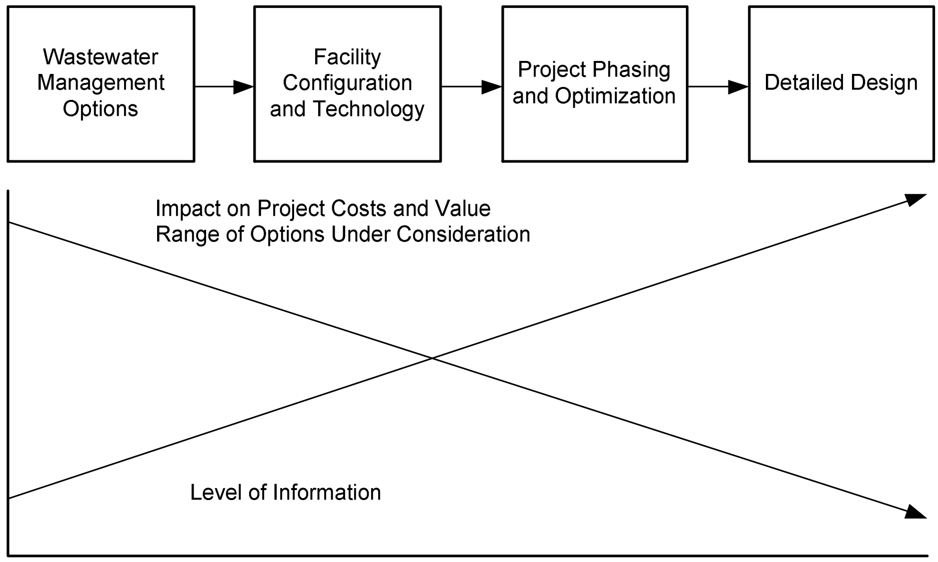



**Figure 1.1.** Impacts and projected costs decrease as project proceeds while level of information increases (adapted from Daigger et al., 2011).

In that sense, from the previous statement, as earlier the right decisions are taken in a project, higher is the capacity to maximize our influence in the process and higher the positive impacts if we carry out the proper decision-making process. Therefore, more attention has to be paid at the conceptual design level in order to ensure better results at all levels (economic, social, environmental, technical and legal). Decisions made during the conceptual design stage became, then, of the paramount importance to achieve the best WWTP option. For this reason, a methodology capable to integrate a proper assessment of alternatives in the earliest project phases should be the best tool to improve the selection of the most suitable options during conceptual design.

Nevertheless, as indicated in figure 1.1, there is a lack of detailed information available during initial stages, which makes that only simple models may be used. Thus, all information and models required during the decision-making process in this phase have to be robust, well-organized and reliable in order that our decisions could maintain their consistency and quality.

Therefore, the integration of new concepts and innovative disciplines within the water field (environmental, social, legal, economic ...) has to fit and taken into account in a facility. The multidisciplinary integration of knowledge from different nature during the decision-making process has to enable a better understanding of this complex sector. Therefore, we are realizing how the development of innovative tools to meet all this current wastewater-related knowledge can help us to find the proper solutions to provide the necessary answers to the current challenges in the wastewater management. In that sense, expert systems with the capability to integrate and handle properly information of different nature are a promising option.

### 1.3. SUPPORTING THE DECISION-MAKING PROCESS

The complexity of environmental problems makes necessary the development and application of new tools capable of processing not only numerical aspects, but also experience from experts and a wide public participation, all which are needed in the decision making process. Therefore, the selection of an appropriate technique for the decision-making in complex processes is crucial for achieving optimal results. A lot of effort, therefore, has been devoted to developing more efficient methodologies.

In the last decades, mathematical/statistical models, numerical algorithms and computer simulations have been used as appropriate means to gain insight into environmental management problems and provide useful information to decision makers (Poch et al., 2004). However, the complexity of wastewater treatment systems require other approaches than a straightforward application of conventional numerical models to look for optimal management when (1) the process state of the WWTP is far from its normal operation and (2) reasoning with qualitative information is essential to deal with problems. For this purpose, a wide set of scientific techniques have been applied for a long time to solve environmental management problems with good results. The integration of these different techniques to deal with more complex systems has led to the development of the expert systems, and specially the so-called Environmental Decision Support Systems (EDSSs).

### 1.3.1 Environmental Decisions Support Systems (EDSS)

Decision Support Systems (EDSS) are tools proposed to enhance the decision making process. For environmental processes, they can be described as EDSS (Environmental Decision Support Systems). The application of decision support systems to environmental systems was initiated in the 80's (Guariso and Werthner, 1989; Rizzoli and Young, 1997) with the aim of providing assistance to decision making beyond the help offered by mathematical models (they have severe restrictions to incorporate qualitative knowledge) and simultaneously, improving what might be a simple accumulation of experience difficult to manage. Nowadays several successful developments and applications of EDSS can be found on literature (Hamouda, 2009). EDSS can be defined as intelligent systems that integrate different tools from different disciplines and help reduce the time needed to make decisions, improving the consistency and quality of them (Cortés et al., 2000; Alemany et al., 2005). From an operational point of view, EDSS can also be defined as an interactive, flexible and adaptable tool that can link numerical and algorithmic methods to artificial intelligence techniques, GIS and environmental ontologies (Haagsma and Johanns, 1994; Comas et al., 2003; Cortés et al., 2001).

#### 1.3.1.1 What is an EDSS?

Environmental Decision Support Systems (EDSSs) are among the most promising approaches to confront complexity. The fact that different tools (artificial intelligence techniques, statistical/numerical methods, geographical information systems, and environmental ontologies) can be integrated under different architectures confers EDSSs the ability to confront complex problems, and the capability to support the decision making processes

EDSSs are inherently integrated (statistical/numerical methods, environmental ontologies, …), usually consisting of various coupled models, databases, and assessment tools capable of supporting complex decision making processes through an accessible computer interface that presents results in a readily understandable form. (Shim et al., 2002; Huang G.H. 2010; He et al., 2006; Matthies et al., 2007). Therefore, EDSS are gaining interest as promising approaches to confront the aforementioned complexity within the wastewater management sector.

EDSSs allow (1) to manage huge volumes of data; (2) to handle expert knowledge; (3) to tackle the uncertainty of data and knowledge; (4) to integrate both data and knowledge, through different models, into a software; (5) to accurately evaluate multiple alternatives; (6) to diagnose an abnormal situation and propose options to solve this problematic event and (7) to provide objective offline/online proposals. Moreover, the EDSS capabilities go beyond supporting the decision-making process. What an EDSS contributes is not only an efficient mechanism to find an optimal solution, given a set of preferences, but also a mechanism to make the entire process more open and transparent. Environmental issues affect all of us, so they belong to a set of critical domains where wrong management decisions may have high social, economic and ecological consequences. In this context, EDSS are tools designed to cope with the multidisciplinary nature and with complex environmental problems. Therefore, they can be used to justify multi-criteria decisions of policy-makers (transparency) more than making real decisions, and provide to end-users a tool to play with "what-if" scenarios, to explore the response surface and the stability of the solution in order to improve the consistency and quality of decisions (McIntosh et al., 2011).

EDSS are developed to help the different agents involved in the wastewater treatment process (from engineers to administration and authorities) in the design and assessment of WWTPs. Also, EDSS are expected to be useful for other stakeholders, as well as students who wish to learn about the principles and methods used. Therefore, the main purpose of the developed EDSS is threefold:

1. To encourage the application of more integrated methods of assessment in order to improve decision-making during the WWTP conceptual design; Establishing clear principles and approaches, so that the assessments are both more reliable and more consistent;

2. To provide a general source for the different agents involved in assessments, this will help them save time in searching and evaluating useful data and methodologies.

3. To bring support to our decisions rationalizing expert and bibliographic explanations in all steps through the WWTP design or retrofit.

#### 1.3.1.2 Why should we use EDSSs?

The use and application of EDSS for planning, design, operation and control offer several advantageous features, which are especially relevant for the complex management of environmental problems and systems, among them:

- Their ability to acquire, represent and structure the knowledge, being able to process the uncertainty in both data and knowledge.
- The ability to separate data from models, and therefore the possibility of working in more general and wider spectra.

- The ability to work with the spatial and temporal dimensions.
- The ability to provide expertise knowledge and to incorporate specific knowledge bases.
- The ability to provide objective responses, both off-line and on-line.
- The ability to be used for diagnosis, planning, management and optimization.
- The ability to help the user during the problem formulation and selection of methods and models for their solution, allowing the assessment of different alternatives.

EDSSs incorporate an explicit methodology for decision making based on a set of theoretical principles, justifying the "rationality" of the procedure. Thanks to this rationality, the EDSS:

1. May provide solutions to complex problems,
2. Allow us to face issues where the experience provides essential and/or important support to find a solution,
3. Reduce the time of the problem identification step, and the amount of time necessary to reach a decision and
4. The consistency and quality of these decisions is improved.

### 1.4. TOWARDS AN INTEGRATED ASSESSMENT

One of the things that are evolving more rapidly in the selection of the best treatment alternative is the process of evaluation. Currently, it is not just to meet criteria for water quality at the effluent, but, as said previously, the process must be optimal with respect to a set of sustainability criteria. The three pillars of sustainability are economic, environmental, and social. Sustainability interfaces with economics through the social and ecological consequences of economic activity. Thus, with the change of paradigm towards integrated assessment the goal is to maximize the benefits of the whole system as a single unit and not focusing on the improvement of single elements independently. Another issue is to consider different types of environmental impacts, meaning that improving the quality of the rivers (e.g. by increasing energy use) does not ends up with endangering other impact categories (e.g. global warming). In this sense, sustainable treatment processes can be defined as treatments which must comply with the three aforementioned pillars and support and enhance the sustainability of the whole treatment system.

#### *Environmental criteria*

Nowadays, society demands that all processes, products or services must be also analyzed from an environmental point of view (Gallego et al., 2008) and also, many other social impacts have to be considered, from odors, noises potential and visual impact to more detailed impacts highly difficult to analyze, as Life Cycle Analysis (LCA) of the wastewater process. All of them have to be taken in account in order to proportionate objective and consistent results. One of the most used environmental indicators is LCA, a methodology encompassed under the concept of Life Cycle Thinking (LCT), which considers the process system under a holistic perspective while avoiding the shifting of the pollution from one life cycle stage to another, from one geographic area to another and from one environmental compartment to another. The consideration of LCT during the decision-making can improve substantially the coherency and efficiency of processes.

### *Economic criteria*

Economic research into the design and implementation of policies for the efficient management of water resources has been emphasised by the European Water Framework Directive (Directive 2000/60/EC). The efficient wastewater treatment management requires determining WWTP processes in social and economic terms and incorporating this information into the decision-making process. In that sense, the incorporation of methodologies for economic valuation is necessary in order to integrate the economical part and enable a wider vision of the problem.

Cost-Benefit Analysis (CBA): The most widely accepted instrument to assess any project at economic level. In this context, among the number of methodologies available which can be used as support instruments for the decision makers, cost-benefit analysis (CBA) is nowadays between the most accepted (Molinos-Senante et al., 2011). In the context of the Water Framework Directive, the CBA is used to identify cases where the adoption of measures for achieving a good water quality in lakes and rivers involves a disproportionate cost. It is a tool to support rational and systematic decision-making, and is made to compare the economic viability associated with the implementation of various proposals. Using this methodology the benefits of each proposal are compared with their costs by using common analytical methodology.

Cost-Benefit Analysis evaluating environmental externalities: This technique allows the consideration in economic terms of the environmental benefits of treating wastewater. This methodology quantifies the theoretical benefits of avoiding the discharge through a set of pollutants (COD, BOD, TSS, nitrogen and phosphorous) and explores the real and hidden benefit of WWTPs. Because these benefits are difficult to calculate since they are not determined by the market, economics have made important efforts in order to estimate the monetary value of them (Garrod & Willis, 1999). In the specific context of wastewater treatment, Hernández-Sancho et al., (2010) have adapted the pioneering methodology developed by Färe et al., (1993) in order to quantify in economic terms the environmental benefits derived from wastewater treatment.

### *Technical and social Criteria*

Current legislation placed technical issues (related to WWTPs) as reliability, removal efficiency, process optimization, and similar at higher-level of importance in order to assure that a WWTP effluent accomplishes the required water quality in each scenario. Therefore, parameters related to technical criteria became essential as plant managers and society must rely on them to keep their natural resources undamaged.

In this sense, all technical parameters that allow the prediction and estimation of the water characteristics after any of the existing treatments should be incorporated during the decision-making process. And, also, a wide range of studies and research must be done in order to cope with all possible variations in the estimations, including the effort to validate the incorporated data with real cases and different knowledge sources.

Moreover, the consideration of qualitative data is becoming crucial in order to introduce expert knowledge within our decision-making process. There are also a set of variables difficult to quantify which undoubtedly also need to be considered. In that sense, data about process robustness, ease of operation, frequency of problems, need for specialized staff, … must be incorporated in the evaluation, and therefore, a set of ranges to express these values must be included. Moreover, the social vector within the plant selection and assessment must to be carefully considered, and those factors that could affect the WWTP neighborhood (odor potential, noises, visual impact ...) have to be considered. Thus, those alternatives contributing to the community wellness, acceptation and positive perception of the plant have to be promoted and valued accordingly.

## 1.5 INTEGRATED ASSESSMENT, WWTPS AND EDSS: A NEW APPROACH.

The results from these different indicators and methodologies undoubtedly might provide a wide, and almost all the required, variety of information in order to select WWTP alternatives using a multidisciplinary view. Thus, depending on the end-user objectives and priorities, methods ranging from classification algorithms to multi-criteria analysis methods can be applied to these specific results or outputs and allow a comprehensive selection of WWTP alternatives. Therefore, a tool able to integrate all these indicators and methodologies in an intuitive and easy way is required. Therefore, in the framework of the NOVEDAR project an EDSS was developed to meet these requirements

The multidisciplinary integration of knowledge has to enable a better understanding of this complex sector. In this sense, the EDSS built in this thesis is a clear an example of the development of a decision support system for the conceptual design and selection of WTTPs configuration taking into account this multidisciplinary approach. Therefore, with such capabilities the EDSS is able to face with the existing XXI century challenges: i) improve water quality to reach reclaimed and discharge water requirements; ii) increase the recycling and enhance product recovery; iii) Minimize and valorize the sludge production and iv) minimize the energetic dependence and operational costs in order to obtain a sustainable treatment process; ... Therefore, supporting the decision-making with the combination of conventional techniques and methodologies with innovative indicators, under the structure of an expert system (Environmental Decision Support System), was an opportunity to build a real support tool to tackle those challenges, taking into account the integrated assessment and the sustainability paradigm, during the decision-making process.

# Chapter 2

## Objectives

*In this chapter, the main objectives and sub-objectives of the thesis are described*

**PhD THESIS**

## THESIS OBJECTIVES

The development of the NOVEDAR_EDSS is performed under the project "Conception of the WWTP of the XXI century". Thus, the aim of the project goes beyond the development, implementation and improvement of innovative technologies. The EDSS is an ambitious approach to integrate the new concepts and innovative disciplines within the water field to fit them globally in the WWTP of the XXI century (Figure1.2).

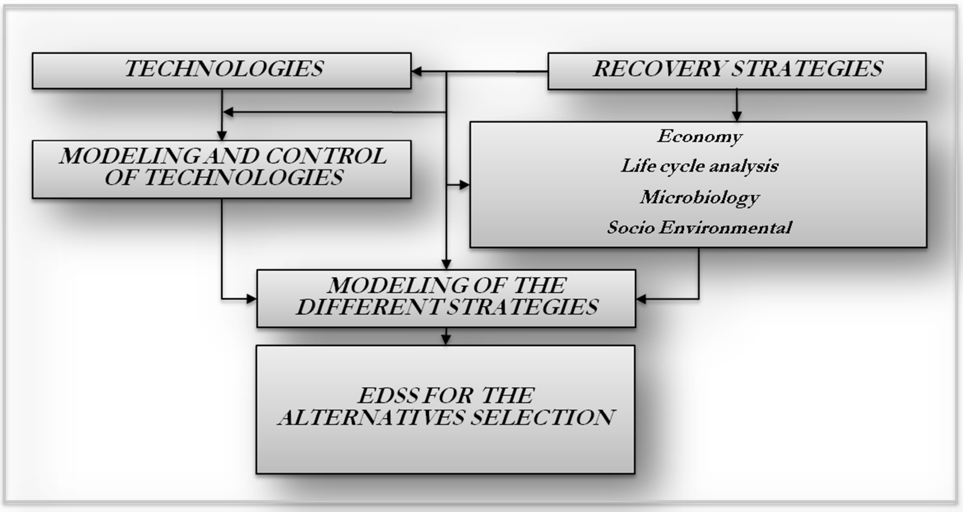



**Figure 1.2.** NOVEDAR_Consolider project scheme (http://www.novedar.com/en/project.asp).

The present thesis, developed within the NOVEDAR_Consolider project, aims to develop an EDSS. Hence, The main objective pursued in this thesis targets the development of a systematic conceptual design method for WWTP using multiple objectives, which supports decision making when selecting the most desirable option amongst several generated alternatives. This research work contributes with an innovative approach combining techniques from different disciplines such as: a hierarchical decision approach, multi-criteria decision analysis, preliminary options screening, knowledge extraction and recursive evaluation.

Moreover, this approach will become the required groundwork to develop and implement further integrated assessment methodologies and emergent technologies. To achieve this main objective, especial features for the development methodology and the EDSS itself must be considered:

1) The methodology has to be able to confront the complexity associated with the selection of WWTPs according XXI century challenges and the current sustainability paradigm.

2) The application of the methodology must provide an EDSS sound and realistic.

3) The appliance of the EDSS into full-scale facilities must be feasible, decision support must be easy to understand and they have to provide useful information in terms of assessment, selection and comparison of WWTP alternative options.

4) The EDSS to be developed must be easily extended to the other wastewater treatment technologies, methodologies and models involved in the NOVEDAR_Consolider project.

Hence, the development of the NOVEDAR_EDSS is related to the following sub-objectives:

a) The selection of the most appropriate methodology to develop the EDSS.
b) The application of this methodology to develop the NOVEDAR_EDSS.

This step procedure (3. Building the NOVEDAR_EDSS) must be conducted whilst bearing in mind the purpose of full EDSS.

# Block III

# Methodology

## Building and operating the NOVEDAR_EDSS

*Two chapters depict the Building (Chapter 3) and the Operation (Chapter 4) of the NOVEDAR_EDSS following the different stages based in the methodology proposed by Poch et al., 2004 for the development and operation of environmental decision support systems.*

# Chapter 3

# Building the NOVEDAR_EDSS

**PhD THESIS**

**This chapter formed the basis of the following publications:**

**M. Garrido-Baserba**, R. Reif, F. Hernández and M. Poch (2012). *A novel knowledge-based methodology for generating suitable WWTP process flow diagrams*. Accepted by Journal of Environmental Management. DOI: 10.1016/j.jenvman.2012.08.013

**M. Garrido-Baserba**, R. Reif, I. Rodriguez-Roda and M. Poch (2011). *A knowledge management methodology for the integrated assessment of WWTP configurations during conceptual design*. Water Science and Technology 66 (1), 165-172

**M.Garrido,** R. Reif, M. Poch. *Development of a EDSS for the generation of WWTP configurations alternatives.* In proceedings of the WATERMATEX. 8th IWA Symposium on Systems Analysis and Integrated Assessment. San Sebastián, Spain. 2011

**M.Garrido**, I. Rodríguez-Roda, X. Flores, M. Poch*. Development of a EDSS for the generation of WWTP configurations alternatives.* In proceddings of the International Congress of Environmental Modeling and Software (EMSS2010) Intelligent Environmental Decision Support Systems. Ottawa, Canadá. 2010

**M.Garrido**, I. Rodríguez-Roda, M. Poch. *Development of the NOVEDAR_ EDSS for the selection and integrated assessment of WWTPs alternatives.* Oral contribution at Water & Industry of the IWA specialist International Conference. NOVEDAR workshop. Valladolid, Spain. 2011

**M.Garrido**, X. Flores, M. Poch. *A Decision Support System to Face New Challenges in the Selection of WWTP Alternatives.* Oral contribution. In proceddings of IWA Specialist Conference "Water and Wastewater Treatment Plants in Towns and Communities of the XXI Century: Technologies, Design and Operation". Moscow, Russia. 2010

**M.Garrido,** X. Flores-Alsina, I. Rodriguez-Roda, M. Poch. *Wastewater Treatment Alternative Selection Using knowledge-based Methods and Multi-criteria Evaluation.* In proceedings of the First Spain National Young Water Professional Conference 2010 (SNYWP 2010). Barcelona, Spain. 2010

**M.Garrido**, X. Flores, M. Poch*. Small Wastewater System selection using knowledge-based methods and multi-criteria evaluation.* Poster contribution. IWA conference on Sustainable Solutions for Small Water and Wastewater Treatment Systems (S2Small2010). Girona, Spain. 2010

# 3. Building the NOVEDAR_EDSS

This chapter can be considered the core of the thesis since it explains how the NOVEDAR_EDSS has been designed and built. How a particular EDSS is build will vary depending on the type of environmental problem and the type of information and knowledge that can be acquired. Although there is not a unique methodology to develop an EDSS, some similarities have been found in EDSSs developed previously. In this respect, Poch et al. (2004) proposed and EDSS development procedure general enough that intended to cope with any kind of EDSS deployment. According to this methodology, the EDSS proposed phases are based in six levels (Figure 3.1): **1)** Problem Analysis; **2)** Data collection and knowledge acquisition**; 3)** Data and knowledge analysis **4)** Model selection; **5)** Model implementation and integration; and **6)** Evaluation and validation of the EDSS.

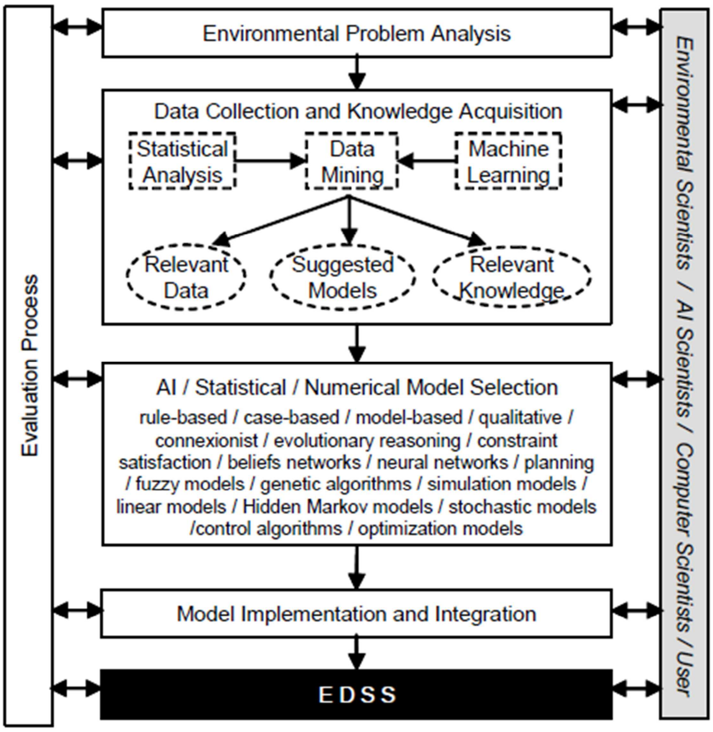



**Figure 3.1.** Development of an EDSS (modified from Cortés et al., 2000).

Although the development of this EDSS is based on the aforementioned methodology proposed by Poch et al. (2004) several modifications were introduced in order to adapt the methodology to our environmental problem. These variations, along with recommendations to build the EDSS, are explained throughout chapter 3.

## 3.1. Environmental problem analysis

The environmental problem must be defined in the first step. This definition is based on the characterization of the domain, the study of the background and the current state of the problem. This analysis allows both (1) definition of the objective of the EDSS and (2) identification of what is required to solve the environmental problem. For this reason, and focusing on the ultimate objective of EDSS, the domain analysis started with a study of the current state of wastewater treatment technologies and plant configuratioms. This study allowed the identification and definition of (1) the particularities of the wastewater treatment nowadays (3.1.1. Wastewater treatment considerations), and (2) the characteristics of the technologies available to treat wastewater from agglomerations of 50 p.e, to cities over 1.000.000 p.e (3.1.2. Wastewater treatment technologies). Afterwards, and focusing on the objective of the integrated assessment, an in-depth studiy and the design of suitable methodologies for the EDSS was conducted on the economics, Lifecycle analysis and technical & operational multicriteria. Finally, using all this information the environmental problem to be solved by the EDSS was identified and the decision-making support granted.

### 3.1.1 Waste water treatment considerations

Current complexity involved in wastewater treatment plants design is arising as the XXI century sets new goals and regulations leading towards a more sustainable plant design. New challenges and constraints are appearing in order to design and select the most suitable WWTP. In this sense, the developed EDSS must try to handle and overcome this current complexity facing the following aspects:

1) Firstly, treatment processes has been steadily growing and there is a large number of treatment technologies which potentially can be implemented for the very same case. These alternatives involve conventional (Oxidation ditch, trickling filters, plug flow ...), small communities' technologies (Wetlands, green filters, peat filters …), and emergent technologies (granular processes, Anammox, RBpM, Hibrids ...). Moreover, different options and multiple combinations between units exist in other sections of a WWTP: Sludge, Tertiary, Primary and Pre-treatment, Odours and, even, Head returns.

2) Secondly, the conceptual design of WWTP is complex issue because exists a large number of potential solutions that we might consider in order to maximize the overall benefits. Very new, or conventional, technology has its own characteristics and interrelations with other technologies and they have to be taken in account. Therefore, the existing

interactions among these technologies, makes difficult the establishment of compatibilities amongst the units comprising the flow diagram e.g. (Hybrid processes, complementary tertiary treatments ...) and the selection of an optimum treatment train sequence.

3) The large number of possible scenarios facing current plants can influence the requirements and characteristics of the technologies composing it. Therefore, conditions as water scarcity, high flow variations, winter-summer seasonality, reuse purposes, discharge in sensitive areas, space limitation and other conditions can higly affect the design of the plant.

4) Complexity related during the selection of the most appropriate technology, as it is necessary to integrate technical (i.e. engineering, natural-based treatment technologies, environmental issues ...), economic and ecological aspects with social sensibilities (i.e. municipalities, ecological groups ...). This approach requires the use of qualitative and quantitative data and knowledge. Thus, the design of WWTPs requires the use of integrated assessment methods in order to include different types of objectives at the same time i.e. environmental, economical, technical, and legal.

Thus, WWTP design and selection of the most appropriate wastewater treatment plant alternative is becoming an extremly complex activity where many decisions have to be taken into acount and many types of information need to be handled with clearnes and objectivity to provide the proper solution. Thus, it is necessary the development and application of integrative tools capable of processing not only deterministic data from technical and economic models, but also heuristic knowledge from experts and social agents.

Once the main considerations related to the problem analysis are shown, it is necessary to identify those elements, that properly combined, could solve, or be a part of the solution of the aforementioned problems. The next paragraphs offer and overview of the two main groups of technologies that should became part of the solutions.

### 3.1.2. Wastewater treatment technologies

Wastewater technologies can be divided in two main groups: Small wastewater treatment plants (SWWTP), and medium and large plants (WWTPs). Both have their own specifications that must be taken into account in order to design the proper EDSS system to include and characterize them properly.

The main particularities of wastewater treatment in the case of small communities are the scarce availability of economic, human and technical resources to guarantee the correct functioning of these facilities. Therefore, to address the common problems observed in small wastewater treatment plants, technologies for these facilities have to fulfil the following requirements (EPA (1992); Alexandre et al., (1998); EPA (1999); Collado et al., (2003)):

a) Economic to construct and operate.

b) Simple to operate and maintain.

c) Low environmental impact.

Those techniques known as low-loaded involve processes which purify by means of fixed film cultures on small media (i.e. constructed wetland and intermittent sand filter) or suspended growth cultures which use solar energy to produce oxygen by photosynthesis (i.e. waste stabilization pond). Low-loaded technologies can be distinguished from high-loaded techniques by the fact that this type of facility can operate without electricity. Another feature of low-loaded techniques is that applied surface loads are very low (European Community (2001)).

On the other hand, medium and large WWTP use to belong to the typology of high-loaded technologies. The principle of high-loaded technologies is to operate on a reduced surface area in order to intensify the naturally-occurring phenomena of organic matter transformation and destruction. The aeration process consists of mixing and stirring raw sewage with recycled activated sludge, which is bacteriologically very active. Aerobic degradation of the pollution takes place by thoroughly mixing the purifying micro-organisms and the influent to be treated. Then, "purified water" and "purifying sludge" phases are separated. However, other systems like biofiltration or hybrid systems, which their treating capacity is due to biofilm degradation processes, are also gaining interest.

## 3.2. Data collection and knowledge acquisition

Once the environmental problem analysis is finished, the data collection and knowledge acquisition phase begins. This stage involves the acquisition and analysis of the required data and knowledge in order to then propose a range of problem solutions. Data and knowledge required to identify and solve the environmental problem can be acquired from different sources: technical and scientific literature, site visits and expert interviews. All of them were used during the EDSS knowledge acquisition phase. This ensures that empirical, theoretical and historical information will be included within the created knowledge bases. Thus, a set of knowledge bases was designed to handle and collect all the required information (**3.5.2.**

**Knowledge-Based System**) The encapsultation of different sources facilitates the integration of a plurality of views, perspectives and goals from all of the disciplines involved in resolving the environmental problem (Turon et al., 2004).

In this sense, a variety of sources were used for the development of the different knowledge bases (Figure 3.2). Taking advantage that NOVEDAR_Consolider project accounts with the cooperation of 9 Spanish and 2 Dutch research groups, 29 relevant water companies in the water sector and 14 public entities related to the water management, higly valuable knowledge and expertise was extracted from these remarkable sources. In this sense, the knowledge was extracted from interviews with experts and bibliography within the NOVEDAR project, as well as project related engineers, companies and wastewater treatment authorities. Conventional knowledge acquisition methods (scientific and technical literature, congress presentations, ...) were also used.


**Figure 3.2.** Main knowledge sources for the NOVEDAR_EDSS development.

### 3.2.1. NOVEDAR network knowledge acquisition

An overview of the knowledge acquired for each of the main Novedar partners through several interviews, site visits, and later information exchange is illustrated in this section. The exact knowledge acquired for any of the following mentioned technologies and methodologies can be consultated using the attached CD with the complet set of KBs implemented in the EDSS (*see **folder S-KB-U** to get the maximum level of detail*) or, even, all basic information (related to the included technologies) can be directly checked using the NOVEDAR_EDSS software within the section libraries (**4.3.3.1 Libraries**). Therefore, the list with the research centers related to the NOVEDAR project that contribute, with their expertise, in this knowledge acquisition phase can be found in the following paragraphs, at the same time that the knowledge field or specific technology characterization obtained from them is also listed.

**Universidad de Santiago de Compostela (USC).** Main group meetings were held on the May 7th-9th, 2009; December 13-17th, 2010; and November 7-8th, 2011.

***Involved NOVEDAR members***: *Dr. Juan M. Garrido, Dr. Juan Lema, Dr. Marta Carballa, Dr. Francisco Omil, Anuska Mosquera and Ramón J. Méndez.*

- Sharon and Anammox processes
- Membrane Bioreactor processes (MBR)
- Data related to micro contaminants removal in some technologies
- Sequential Batch Reactors (SBR) based on granular sludge.
- Anaerobic reactors for urban wastewater (pre) treatment

Later on, a **project stay** (*October 2011 to March 2012*) to implement the Life Cycle Assessment (LCA) methodology within the EDSS was carried out at USC. The responsible professor of the stay was *Dr. Almudena Hospido and Dr. Mª Teresa Moreira. The professors or associated professors as Dr. Gumersindo Feijo and Gonzalo Rodríguez also participate actively in the process.*

- LCA methodology implementation for WWTPs (**See also section 3.5.7.1. LCA models implementation**)

**Universidad de Cantabria (UC).** Meeting held on June 15th -16th, 2009.

***Involved NOVEDAR members:*** *Dr. Iñaki Tejero, Rúben diez and Dr. Loredana de Florio, Dr. Enrique Nebot.* The main knowledge incorporation was focused in the advanced biological treatments that the research center is developing (Fixed bed biofilm reactors, Membrane biofilm reactors, Membrane aerated biofilm reactors):

- MABR (RBSOM): Membrane Aerated Biofilm Reactor
- BLASF+Mbr/ RBpM (*The acronym definition can be found at S-KB*)
- P-HD-HN (*The acronym definition can be found at S-KB*)
- P-HDNmb (*The acronym definition can be found at S-KB*)
- HPDNmb (*The acronym definition can be found at S-KB*)

**Universitat de Barcelona (UB).** Meeting held on June 4th, 2009.

***Involved NOVEDAR members:*** *Dr. Joan Mata, Dr. Silvia López, Dr. Renato Falçao and Dr. Santiago Esplugas*. The main knowledge field is related to wastewater treatment by means of chemical oxidation (Advanced Oxidation Processes).

- Ozone
- Hydrogen peroxide
- UV
- Photo-Fenton
- Photocatalisis
- Chlorination
- Other tertiary combinations
- Granular Activated Carbon (GAC)
- Other Oxidation processes (combinations)
- Aerobic Granulation technology
- Sludge Treatments processes

**Universidad de Cádiz (UCA).** Meeting held on February 18th-19th, 2010.

***Involved NOVEDAR members:*** *Dr. Jose Abelleira, Dr. Diego Sales, Dr. José M. Quiroga, Dr. José Antonio Perales, Dr. María del Rosario and Dr. Jose L. García.* The knowledge acquisition in this research group was focused on the following typology technologies:

- Thermo-chemical hidrolysis
- Wet Oxidation
- Supercritical Oxidation
- Anaerobic technologies
- Composting typologies

**Universidad de Valladolid (UVa).** Meeting held on the June 17th -18th, 2009.

***Involved NOVEDAR members:*** *Dr. Francisco Fernández- Polanco, Dr. Maria Fernández-Polanco, Dr. Raúl Muñoz, Raquel Lebrero* and Dr. Pedro García Encina. The research of the group is focused on biotechniques for VOCs control, anaerobic processes, sludge minimization and process integration. The selected technologies characterized are the following ones:

- Biofilter
- Trickling filter
- Bioscrubber
- Sludge Air Difusion
- Sludge thermic hidrolysies
- Emergent technologies related with Anaerobic Digestion

**Universidad de Girona (UdG).** *Several meetings a long the project period*

***Involved NOVEDAR members:*** *Dr. Claudia Turón, Dr. Xavier Flores, Dr. Marilós Balaguer, Dr. Jesús Colprim and Dr. María Martin (*Not taking into account the support from those that participate providing the knowledge required for the EDSS development). These UdG researchers participate in the characterization of the following technologies:

- Sequential Batch Reactors (SBR)
- Granular processes
- Sharon and Anammox processes
- Non-conventional technologies (reedbeds, lagoon, wetland ...)
- Conventional technologies
- Membrane Technologies

**Centro de Estudios e Investigaciones Técnicas de Guipuzkoa (CEIT)**. Meeting held on the June 20th -22th, 2011 and during the NOVEDAR summerschool held in the research center. **.** ***Involved NOVEDAR members:*** *Dr. Luís Larrea, Dr. Eduardo Ayesa, Dr. Paloma Grau, Dr. Ion Irizar and Luis Sancho.* The projects offered are base don the application of the most advanced methods in mathematical modelling and experimental analysis for optimizing the design, operation and automatic control. Therefore, all concepts about the design of WWTP that was helpuful for the design of WWTP were acquired. Moreover, decision trees to select the best WWTP configuration using expert knowledge were created in this center. Main knowledge fields acquired:

- Modelling capabilities incorporation (Not yet implemented)
- Membrane bioreactors (MBR) Technologies
- Activated sludge for carbon and nutrients removal
- Sludge and solid waste treatment technologies
- Integrated water management

**Universidad de Valencia (UV).** Short stay from the 27th to 3rd of February, 2011.

***Involved NOVEDAR members***: *Dr. Francesc Hernández, Dr. Ramón Sala and Dr. Maria Molinos Senante.* Main research lines in this center are related to the development of methodologies to optimize the management of wáter resources. The knowledge field that was implemented in order to providethe required feasibility studies and technical and cost efficiency for wastewater treatment proceses were:

- Cost function methodologies
- Cost-Benefit and Cost-benefit taking into account environmental externalities methodologies impplementation.
- Cost modelling for wastewater treatment plants

*Another research center that contributes to this knowledge acquisition phase was the Catalan Institute for Water Research (ICRA).*

**Catalan Institute for Water Research (ICRA).** *Several meetings a long the project period*

***Involved NOVEDAR members:*** *Dr. Manel Poch, Dr. Ignasi Rodriguez Roda, Dr. Joaquim Comas, Dr. Lluís Coromines, Dr. Esther Llorens, (*Not taking into account the support from those that participate providing the knowledge required for the EDSS development). These ICRA researchers contribute to enrich the following topics:

- Life Cycle Analysis
- Green House Emissions
- Small wastewater treatments
- Removal of priority pollutants

### 3.2.2. Basic literature scientific data acquisition

A short overview of the main literature sources that were used for the acqusition of diferent parameters and types of data, from the characterization of technologies to the selection of the most relevant parameters for the assessment WWTPs, is briefly listed. As said previously, the detailed and complet scientific sources used to acquire the knowledge can be found into the complet set of KBs (attached Thesis CD) where includes all source references for each criterion or decision factor for any technology or WWTP-relataed unit (specifically, almost all relevant information can be found at S-KBu and C-KBu). Moreover, those information sources that have been used as reference at any section of the EDSS software can be also found, and correspondegly referenced, in the dialogue boxes displayed in the EDSS interface for any of the characterizing parameters included in all the technologies comprised in the library section (**4.3.3.1 Libraries**).

Thus, the shoredt list of scientific sources listed in the next section is some of the knowledge pillars where to build the rest using more specific data. From this sources, a relevant quantity and high quality knowledge was acquired in order to: i) incorporate higly validated data and knowledge that the scientific community considered trustworthy and accepted as reliable; ii) provide data enabling the comparison of other less reliable sources (pilot plants, specific configurations, special plant features, ...); iii) Allow the comparison of conventional values with those from emergent technologies; and iV) provide a reference point for those users that would consider customize these characterization values.

Therefor in table 3.1, some of the main bibliographic sources that were used to fulfill the aforementioned KBs and supported the selection of the most relevant parameters implemented are displayed.

**Table 3.1.** Partial table with some of the main objectives, criteria and references.

| OBJECTIVE | CRITERION | REFERENCES |
|---|---|---|
| Technical Design | *Plant design* | Metcalf & Eddy., 2003; CEDEX, 2009; Cortacans, 2008; Hernández, 2001; Isla de Juana, 2005 |
| | *Robustness* | U.S. EPA,1979; WEF, 1998; Vanrolleghem and Guillot, 2002, Flores et al. 2006; Novedar_interviews&literature |
| | *Flexibility* | Vanrolleghem and Guillot, 2002; Flores et al. 2006; CEDEX and CENTA 2010; Novedar_interviews&literature |
| | *Control over the process* | Stephanopoulos, 1984; CEDEX, 2008; Henze et al. 2008; Novedar_interviews&literature |
| | *Reliability* | Balaguer, et al. 2007; EDSS-PSARU, 2002; Metcalf & Eddy., 2004; Novedar_interviews&literature |
| | *Safety* | Balaguer, et al. 2007; Novedar_interviews&literature |
| | *Settling efficiency* | Gernaey et al., 2006; Balaguer, et al. 2007; Martins et al.,2004; Grady et al.,1999 |
| | *Operation simplicity* | Hamoud, F.M. 1988; Grady and Daigger 1999; Novedar_interviews&literature |
| | *Stability* | CEDEX,2008; Novedar_interviews&literature |
| | *Innovation degree* | Metcalf & Eddy, 2004; Novedar_interviews&literature |
| Environmental Impact | *Visual Impact* | Metcalf & Eddy, 2004; CEDEX, 2008; Novedar_interviews&literature |
| | *Reactants Use* | Meneses, 2010; Rodriguez, et al 2012; Novedar_interviews&lieterature |
| | *Life Cycle Analysis* | Novedar_interviews&literature; Guiné, 2002; Castells et al. 2007; Menseses et al. 2010; Coromines et al 2011, Novedar_interviews&literature |
| Economic | *Construction cost* | US EPA 1982, CEDEX 2008; CEDEX and Centa 2010; Novedar_interviews&literature |
| | *Operating costs* | Vanrolleghem and Guillot, 2002; David W. Pennington, 2005; Esplugas, S. & Matas, J. 2008; Portela, J. 2010; Pasqualino, 2011; J.C Novedar_interviews&literature |
| | *Maintenance* | EPA, 1970; WEF, 1998; Metcalf & Eddy., 2003; CEDEX and CENTA 2010; Novedar_interviews&literature |
| | *Economical benefits* | Novedar_interviews&literature |
| | *Space requirements* | CEDEX 2008, CEDEX and CENTA 2010; Novedar_interviews&literature |
| | *Investment* | Delhoménie, M-C and Heitz, M, 2003; Adrianus van Haandel and Jeroen van |

| | | |
|---|---|---|
| | | der Lubbe, 2007; Novedar_interviews&literature; US EPA 1982 |
| Process sub-products | *Odours* | Shareefdeen et al., 2005; Adams et al., 2004; American Soc.Civil Engin., 1995; Stuetz et al., 2001 |
| | *Sludge* | Hamouda, M.F. 1988; Metcalf & Eddy., 2003; Sevilla, M. et al 2005; Novedar_interviews&literature |
| | *Gas release* | IPPC Guidelines (IPCC, 1997, pp. 6.17-6.28) and Good Practice Guidance (GPG, 2001, pp. 5.14-5.24); NIR, 2010; Monteith 2006; Novedar_interviews&literature |
| | *Noises Potential* | CEDEX and CENTA 2010; Novedar_interviews&literature |
| | *Odor Potential* | Crocker and Scnelle, 1998; Juteat, 1997, and Devinny et al.,1998; Zarook Shareefdeen & Ajay Singh, 2005; CEDEX and CENTA 2010; Novedar_interviews&literature |
| Processes Performance | *Effluent Turbidity* | Metcalf and Eddy., 2003; Henze et al. 2008; Novedar_interviews&literature |
| | *Grease/Grit removal* | CEDEX 2008, CEDEX and CENTA 2010; Metcalf and Eddy., 2003; Novedar_interviews&literature |
| | *Nutrient Removal* | Gujer et al. 2001; EDSS-PSARU, 2002; CEDEX 2008, ACA 2008; Novedar_interviews&literature |
| | *Emergent cont. removal* | Barceló et al, 2006; Carballa et al., 2008, Henze et al. 2008; Novedar_interviews&literature |
| | *TSS removal* | EDSS-PSARU, 2002; Metlcaf &Eddy, 2004; CEDEX 2008; Novedar_interviews&literature |
| | *COD removal* | EDSS-PSARU, 2002; Siegrist et al, 1999, Metlcaf &Eddy,2003; Henze et al 2008 |
| | *Pathogenic removal* | Henze et al. 2008; CEDEX and CENTA 2010; Novedar_interviews&literature |

The data and knowledge required to solve the environmental problem was extracted from the different aforementioned sources. On those cases where there was not a wide agreement between sources the information was corroborated and validated by those experts working in related-topics within the NOVEDAR project network. However and, consequently, expert knowledge is the predominant available information typology.

## 3.3 Data and knowledge analysis

Knowledge obtained in the bibliographic researchwas gathered with that of the interviews and communications between Novedar partners. This information was processed by attempting to identify those aspects that would help us to organize and manage in a specific and efficient way all the knowledge collected.

As a result of information processing, was detected that two domains of knowledge had to be well implemented in the EDSS. 1) The available technologies and all their characteristics, including their suitable combinations and basic design specifications; 2) And secondly, all the information related to the project framework or whatever information was needed to estimate the scenario or initial conditions, as the set of legislatives constraints, economic analysis, environmental considerations and other required information.

### 3.3.1 Technology domain

For the first domain of knowledge the potential technologies being sensitive to be implemented were identified and characterized succesfuly within the EDSS framework (Table 3.2). These technologies are related to the different sections that compouse almost all typies of WWTPs: Pre-treatment, Primary, Secondary, Tertiary, Sludge, Head return and Odour treatment (Metcalf and Eddy, 2004). Moreover, the main parameters that would enable the characterization of each technology were also identified. Those characteristcs or specifications that were available for almost all technologies (i.e. COD removal efficiency) were the most selected as they provide an important common point for comparison between technologies. Finally, almost 288 technologies with their specifications were implemented. The detailed list of parameters involving the technologies characterization can be found at section **3.5.2 Specification Knowledge Base (S-KBs)**. Furthermore, from the diferents parameters selected, different groups or parameters clusters were created in order to categorize them in specific topics. The categories are Influent, Effluent, Sub-products, Impacts, Costs, Operation and Technical (**see section 3.5.2.1**). This categorization is intended to simplify the EDSS structure and organization and, also, to clarify the selection procedure according to the end-user parameter priorization.

The large amount information acquired is not too easy to handle and has to be thoroughly understood and planned. Therefore, the final point in order to manage all this knowledge was not solved through the creation of a single knowledge base including all technologies information. To deal with this dilemma information, related to other areas that are also essential to support the WWTP selection process, a set of different knowledges bases with different specifications and characteristics was created.

Finally, the knowledge was organized and compiled within 11 knowledge bases. The created are counted briefly (six KBs arerelated for the first domain):

- 1 group of 3 KBs related to the technologies characterization **(Section 3.5.2.1 Specification Knowledge Base (S-KBs).** In **Section 3.5** further details about the characterization process are given and main differences between those 3 KBs.
- 1 group of 3 knowledge matrices about technologies compatibility and design structure **(Section 3.5.2.2 Compatibility Knowledge Base C-KBs**)

### 3.3.2 Context and scenario domain

For the second domain, a set of KBs and matrices were also implemented for the following topics. **See section 3.5.2.3 Environmental Knowledge Base (E-KBs)**.

**Matrices (See CD Thesis):**

1.a) Shadow prices for both economic Cost-Benefit methodologies implemented.

1.b) Emissions and characterization factors for the Life Cycle Analysis from CML200 Ecoinvent

1.c) Estimation of heavy metal concentration in biosolids.

**Knowledge Bases (See CD Thesis):**

2.a) European Framework

2.b) Spanish Water Reuse Legislative Framework

2.c) Spanish discharge Legislation

2.d) European and Spanish Sludge Legislation

Taking into account that the interaction between KBs is required this group was specifically designed to share and transform the knowledge in a functional manner in order to solve our conceptual design problem. Therefore, these requirements and the large number of KBs lead to the creation of Knowledge-Based System (3.3. Knowledge-Based System).

| MU:1 | PRIMARY |
|---|---|
| **sMU: 1,1** | **COARSE RETENTION WELL and GRINDER** |
| 1,1,1 | Bivalve Electro-Hydraulic Grab |
| 1,1,2 | Well with Grinder |
| **1,2** | **COARSE SCREENS PRETREATMENT** |
| 1,2,3 | Coarse Screens Hand-Cleaned |
| 1,2,4 | Mechanically Chain-Driven Screens |
| 1,2,5 | Mech. Reciprocating Rake Screen |
| 1,2,6 | Mechanically Catenary Screen |
| 1,2,7 | Mech. Continuous Belt Screen |
| **SM: 1,3** | **FINE SCREENS PRE-TREATMENT** |
| 1,3,8 | Fine Screens Static Wedgewire |
| 1,3,9 | Fine Screens Drum Screens |
| 1,3,10 | Fine Screens Step Screens |
| **1,4** | **COARSE SOLIDS REDUCTION** |
| 1,4,11 | Comminutors |
| 1,4,12 | Macerators |
| 1,4,13 | Grinders |
| **1,5** | **DEGRITTING/DEGREASING** |
| 1,5,15 | Horizontal-Flow Grit Chambers |
| 1,5,16 | Rectangular Horizontal-flow grit chamber |
| 1,5,17 | Aerated Grit Chamber |
| 1,5,18 | Vortex-type Grit Chamber |
| 1,5,19 | Solids (Sludge degretting) |
| 1,5,20 | Bridge Grit and Grease Removal |
| **1,6** | **COMMINUTORS AND MACERATORS** |
| 1,6,21 | Comminutors (Post Grit Chamber) |
| 1,6,22 | Macerator (Post Grit Chamber) |
| **1,7** | **FLOW EQUALIZATION** |
| 1,7,23 | Flow equ. Continuous Rapid Mixing |
| 1,7,24 | Flow equalization Mixing |
| 1,7,25 | Flow equalization Flocculation |
| **1,8** | **SMALL WWT SYSTEMS** |
| 1,8,26 | Imhoff Tank |
| 1,8,27 | Septic Tank |
| 1,8,28 | Anaerobic Pond |

| MU:2 | SECONDARY |
|---|---|
| **SMU:2,10** | **CONVENTIONAL ACTIVATED SLUDGE** |
| 2,10,33 | Complete Mix |
| 2,10,34 | Complete Mix + Nitrifi. |
| 2,10,35 | Conventional Plug Flow |
| 2,10,36 | Step Feed (Plug Flow) |
| 2,10,37 | Extended Aeration |
| 2,10,38 | Oxidation Ditch |
| **2,11** | **NITROGEN REMOVAL** |
| 2,11,39 | Ludzack-Ettinger |
| 2,11,40 | Modified Ludzack-Ettinger |
| 2,11,41 | Step Feed (N removal) |
| 2,11,42 | Oxidation Ditch (N) |
| 2,11,43 | SBR (N removal) |
| 2,11,44 | Bardenpho (4 stages) |
| 2,11,45 | Double Stage |
| 2,11,46 | Simultaneos nitrification-denitrif. |
| **2,12** | **PHOSPHOROUS REMOVAL** |
| 2,12,47 | A2-O |
| 2,12,48 | UCT |
| 2,12,49 | PhoStrip |
| 2,12,50 | Modified Bardenpho |
| 2,12,51 | VIP |
| 2,12,52 | SBR (nutrient Removal) |
| 2,12,53 | VIP |
| 2,12,54 | SBR (nutrient Removal) |
| **2,13** | **ATTACHED GROWTH TECHNOLOGIES** |
| 2,13,55 | Trickling Filter |
| 2,13,56 | Trickling Filter + Nitrification |
| 2,13,57 | Rotating Biological Contactor (RBC) |
| 2,13,58 | RBC + Nitrification |
| 2,13,59 | Activ. Sludge Fixed-film packing |
| 2,13,60 | Susp. Pack. Captor and Lipor |
| 2,13,61 | Susp. Pack. Kaldnes |
| 2,13,62 | Fixed packing Ringlace |
| 2,13,63 | Fixed packing Bio-2-sludge |
| 2,13,64 | Submerged attached growth |
| 2,13,65 | Sub. attached upflow Biofor |
| 2,13,66 | Sub. attached upflow Biostyr |
| 2,13,67 | FBBR |
| 2,13,68 | Downflow packed-bed |

| MU:3 | TERTIARY |
|---|---|
| **3,19** | **MICROSCREENING** |
| 3,19,104 | Microscreens |
| **SM: 3,20** | **PHYSICOCHEMICAL TREATMENTS** |
| 3,20,105 | Coagulation/Flocculation |
| 3,20,106 | Chemical Precipitation |
| 3,20,107 | Phosphorus Chemical Treatment |
| 3,20,108 | Laminated Sedimentation |
| 3,20,109 | Micro-Sieve |
| **3,21** | **EXTENSIVE OR LOW-LOADED TREATMENTS** |
| 3,21,110 | Horiz. Surface Flow Construct. Wetland |
| 3,21,111 | Horiz. Subsurface Construct. Wetland |
| 3,21,112 | Vertical Subsurface Constructed Wetland |
| 3,21,113 | HSCW -VSCW Mix of two wetlands tipologies |
| 3,21,114 | Stabilization Pond |
| 3,21,115 | High-Rate Pond |
| 3,21,116 | Airated Pond |
| 3,21,117 | Maduration Pond |
| 3,21,118 | Macrophyte Pond |
| 3,21,119 | Storage Pond |
| **3,22** | **PONDS - EXTENSIVE TREATMENTS** |
| 3,22,120 | Maduration Pond |
| 3,22,121 | Macrophyte Pond |
| 3,22,122 | Storage Pond |
| **3,23** | **FILTERS** |
| 3,23,123 | Conventional Downflow Filter |
| 3,23,124 | Deep-bed downflow Filter |
| 3,23,125 | Deep-bed Upflow Filter |
| 3,23,126 | Pulse-bed Filter |
| 3,23,127 | Traveling-Bridge Filter |
| 3,23,128 | Synthetic-Medium Filter |
| 3,23,129 | Two-stage filter |
| 3,23,130 | Disfilter |
| 3,23,131 | Cloth-media Filter |
| **3,24** | **ACTIVATED CARBON** |
| 3,24,132 | Activated Carbon Adsorption |
| **3,25** | **MICROFILTRATION** |
| 3,25,133 | Microfiltration |

| MU:4 | WP HEAD PLANT RETURNS |
|---|---|
| **4,36** | **RETURNS** |
| 4,36,156 | Anammox |
| 4,36,157 | Partial Nitrification - Anammox |
| 4,36,158 | Nitrifi. Anammox at low temp. |
| 4,36,159 | Canon |
| 4,36,160 | Oland |
| 4,36,161 | Deamonification |
| 4,36,162 | Storage tank |

| MU:6 | ODOUR TREATMENTS |
|---|---|
| **6,48** | **PHYSICAL AND CHEMICAL TREATMENTS** |
| 6,48,264 | Steamers |
| 6,48,265 | Mask Compounds |
| 6,48,266 | Inhibitors |
| 6,48,267 | Neutralizators |
| 6,48,268 | Membranes |
| 6,48,269 | UV Photolisis |
| 6,48,270 | Ozonization |
| 6,48,271 | Adv. Catalitic Oxidation process |
| 6,48,272 | Catalitic Oxidation |
| 6,48,273 | Catalitic Incineration |
| 6,48,274 | Dry Oxidation |
| 6,48,275 | Fenton Oxidation |
| 6,48,276 | Chemical Cleaning |
| 6,48,277 | Condensation |
| 6,48,278 | CRIO-Condensation |
| 6,48,279 | ABSORTION |
| 6,48,280 | Regenerative Adsorption |
| 6,48,281 | Non-regenerative Adsorption |
| **6,49** | **BIOLOGICAL TREATMENTS** |
| 6,49,282 | Trickling fikter |
| 6,49,283 | Bioscrubber |
| 6,49,284 | Biofilter |
| 6,49,285 | Activated Sludge Difusion |
| 6,49,286 | Photochemical Bioreactor |
| 6,49,287 | Rotating Biological Contactor |
| 6,49,288 | Suspended Cell Bioreactor |

| MU:5 | SLUDGE |
|---|---|
| **5,37** | **SLUDGE REDUCTION TREATMENTS** |
| 5,37,163 | Oxic-settling-anaerobic Process (OSA) |
| 5,37,164 | Oxigen Pur |
| 5,37,165 | Descopladors Químics |
| 5,37,166 | Ozone during activated sluge Process |
| 5,37,167 | Lysis-cryptic growth |
| **5,38** | **PRELIMINARY OPERATIONS** |
| 5,38,168 | Grinding |
| 5,38,169 | Degritting |
| 5,38,170 | Blending |
| 5,38,171 | Storage |
| **5,39** | **SLUDGE THICKENING** |
| 5,39,172 | Gravity Thickening |
| 5,39,173 | Flotation Thickening |
| 5,39,174 | Centrifugation |
| 5,39,175 | Gravity-belt Thickening |
| 5,39,176 | Rotary-drum Thickening |
| **5,40** | **SLUDGE STABILIZATION** |
| 5,40,177 | Chlorine Oxidation |
| 5,40,178 | Heat Treatment |
| 5,40,179 | Lime Stabilization |
| 5,40,180 | Alkaline stabilization |
| 5,40,181 | Composting |
| 5,40,182 | Anaerobic Thermophilic Digestion |
| 5,40,183 | Anaerobic Mesophilic Digestion |
| 5,40,184 | Autothermal thermophilic aerobic digestion |
| 5,40,185 | Aerobic Thermophilic Digestion |
| 5,40,186 | Aerobic Mesophilic Digestion |
| 5,40,187 | Pasteurization |
| 5,41 | **SLUDGE CONDITIONING** |
| 5,41,188 | Thermal Conditioning |
| 5,41,189 | Chemical Conditioning - Lime (CaO) |
| 5,41,190 | Chemical Conditioning - FeCl3 |
| 5,41,191 | Chem. Cond. - Anionic Polielectrolit |
| 5,41,192 | Chem. Cond.- Cationic Polielectrolit |
| 5,41,193 | Elutriation |
| 5,41,194 | Freezing |
| 5,41,195 | Ultrasounds |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **1,9** | **PRIMARY CLARIFIERS** | 2,13,69 | Upflow packed bed | | | 5,42 | **SLUDGE DESINFECTION** |
| 1,9,29 | Combination Flocculate - Clarifier | | | **3,26** | **ULTRAFILTRATION** | 5,42,196 | Pasteurization |
| 1,9,30 | Stacked (Multilevel) Clarifiers | **2,14** | **MEMBRANE BIO-REACTORS** | 3,26,134 | Ultrafiltration | 5,42,197 | Long-Term Storage |
| 1,9,31 | Rectangular Tank | 2,14,70 | MBR in Specific Tank | | | 5,42,198 | SLUDGE DEWATERING (II) |
| 1,9,32 | Circular Tank | 2,14,71 | MBR in Aerobic Tank | **3,27** | **NANOFILTRATION** | 5,42,199 | Vacuum Filter |
| | | 2,14,72 | MBR other configuration | 3,27,135 | Nanofiltration | 5,42,200 | Centrifuge |
| | | 2,14,73 | New: Membrane Hibrid | | | 5,42,201 | Belt-filter press |
| | | | | **3,28** | **REVERSE OSMOSI** | 5,42,202 | Filter press |
| | | **2,15** | **GRANULAR** | 3,28,136 | Reverse Osmosi | 5,42,203 | Sludge Drying Beds |
| | | 2,15,74 | New: Biofilter Reactor | | | 5,42,204 | Reed Beds |
| | | 2,15,75 | Aerobic Granular Bioreactor (GSBR) | **3,29** | **REVERSE ELECTRODIALYSIS** | 5,42,205 | Lagoons |
| | | 2,15,76 | New: Hibrid Process | 3,29,137 | Reverse Electrodialysis | 5,42,206 | Electrosmosis |
| | | **2,16** | **HYBRID SYSTEMS** | **3,30** | **ACTIVATED CARBON** | **5,43** | **HEAT DRYERS AND OTHER PROCESSING** |
| | | 2,16,77 | RBpM | 3,30,138 | Activated Carbon Adsorption | 5,43,232 | Flash Dryer |
| | | 2,16,78 | RBSOM | | | 5,43,233 | Spray Dryer |
| | | 2,16,79 | P-HD-HN | **3,31** | **GAS STRIPPING** | 5,43,234 | Rotary Dryer |
| | | 2,16,80 | P-HDNmb | 3,31,139 | Gas Stripping | 5,43,235 | Multiple Hearth Dryer |
| | | 2,16,81 | HPDNmb | | | 5,43,236 | Multiple-effect Dryer |
| | | | | **3,32** | **ION EXCHANGE** | 5,43,237 | Direct Dryers |
| | | **2,17** | **LOW-LOADED TECH.** | 3,32,140 | Ion Exchange | 5,43,238 | Indirect Dryers |
| | | 2,17,82 | Horiz. Surface Flow Wetland | | | 5,43,239 | Alkaline Stabilization |
| | | 2,17,83 | Horizontal Subsurface Constructed Wetland | **3,33** | **ADVANCED TREATMENT** | 5,43,240 | Pasteurization |
| | | 2,17,84 | VSCW Vertical Wetland | 3,33,141 | Ozone/UV | 5,43,241 | Long-Term Storage |
| | | 2,17,85 | HSCW -VSCW | 3,33,142 | Ozone/Hydrogen Peroxide | 5,43,242 | Composting |
| | | 2,17,86 | Stabilization Pond | 3,33,143 | Ozone/ UV/Hydrogen Peroxide | 5,43,243 | Electro-osmosis |
| | | 2,17,87 | High-Rate Pond | 3,33,144 | Hydrogen Peroxide/ UV | | |
| | | 2,17,88 | Airated Pond | | | **5,44** | **THERMAL REDUCTION** |
| | | 2,17,89 | Maduration Pond | **3,34** | **REDUCCTION PROCESSES** | 5,44,244 | Multiple-hearth incineration |
| | | 2,17,90 | Internittent Sand Filter | 3,34,145 | Reduction: Fe zero | 5,44,245 | Fluidized-bed incineration |
| | | 2,17,91 | Buried sand Filter | 3,34,146 | Reduction: Photocatalysis | 5,44,246 | Coincineration with solid waste |
| | | 2,17,92 | Buried Peat Filter | | | 5,44,247 | Vertical Deep Well Reactor |
| | | 2,17,93 | Green Filter | **3,35** | **OXIDATION PROCESSES** | 5,44,248 | Wet Air Oxidation |
| | | 2,17,94 | Aerated Lagoon: Facultative | 3,35,147 | Oxidation: Cloration - ClO2 | | |
| | | 2,17,95 | SGAL: Aerobic flow-through | 3,35,148 | Oxidation: Cloration - ClO3 | **5,45** | **POST-TREAMENT** |
| | | 2,17,96 | SGAL: Aerobic with solid recycling | 3,35,149 | Oxidation: UV | 5,45,249 | Pasteurization |
| | | 2,17,97 | Septic Tank | 3,35,150 | Oxidation: Ozone - O3 | 5,45,250 | Pirolisis-Gasification |
| | | 2,17,98 | Imhoff Tank | 3,35,151 | Oxidation: Potassium Permanganate | 5,45,252 | Radiation |
| | | 2,17,99 | Anaerobic Pond | 3,35,152 | Oxidation: Foto-fenton | 5,45,253 | Chemical Fixation |
| | | 2,17,100 | UASB Reactor | 3,35,153 | Oxidation: Hydrogen Peroxide | 5,45,254 | Acid-Base reaction |
| | | 2,17,101 | EGSB Reactor | 3,35,154 | Oxidation: Cloration - ClO2 | 5,45,255 | Alkaline Desinfection |
| | | | | 3,35,155 | Oxidation: Cloration - ClO3 | 5,45,256 | Encapsulation |
| | | **2,18** | **ANAEROBIC DIGESTION** | | | | |
| | | 2,18,102 | Mesophilic Digestion | | | **5,46** | **SLUDGE STORAGE** |
| | | 2,18,103 | Thermophilic Digestion | | | 5,46,257 | Cement Silo |
| | | | | | | 5,46,258 | Sludge Storage Basins |
| | | | | | | 5,46,259 | Sludge Storage Pads |
| | | | | | | **5,47** | **FINAL SLUDGE** |
| | | | | | | 5,47,260 | Land Application |
| | | | | | | 5,47,261 | Distribution and Marketing |
| | | | | | | 5,47,262 | Chemical Fixation |
| | | | | | | 5,47,263 | Sludge Landfilling |

**Table 3.2**. Exhaustive list of technologies identified and implemented in the Novedar_EDSS.

## 3.4. Model selection

This step in the development of an EDSS consists in the selection of models to represent the data and knowledge acquired in the second step (Poch et al. 2004). Therefore, the next step consists in selecting and creating the set of models that best cover all kinds of knowledge and functionalities required for the decision-making processes. This applies not only to numerical and statistical models, but also to AI methodologies.

This selection must take into account the following aspects (Turon et al., 2006):

a) The aim of the EDSS (i.e. diagnosis, planning, prediction, design ...).

b) The processes involved within the environmental problem.

c) The type of knowledge available: quantitative and/or qualitative

d) The amount of data and knowledge available.

Hence, before the selection of the proper model (**3.4.2. Overview and justification of the model selected**) all these aspects were evaluated (**3.4.1. Considerations for the models selection**). And once the set of models was selected, this stage was completed by choosing the most adequate platform in terms of license cost and software potential.

### 3.4.1. Considerations for the models selection

The aim of the NOVEDAR_EDSS is to provide support for the design and integrated assessment. At first sight the EDSS can be considered a project planning tool because it aims to provide detailed information for the correct decision-making process.

However, the NOVEDAR_EDSS objective can be broadened to other levels; an in-depth study of the processes implemented led to the definition of two types of purposes: (1) comparison of WWTP designs (technical, environmental and economic analysis and assessments); and (2) educational purposes. While the comparison of WWTP plants are based on the implemented functionalities and methodologies in the software, educational purposes are focused on showing in an easy and practical way all the knowledge comprised in the set of Knowledge Bases (**4.3 Decision Support**). This first purpose also allowed the identification of remarkable trends and conclusions that are further explained in the following results chapters (**See Chapter 5, 6 and 7**)

NOVEDAR_EDSS was planned as an offline tool: from offline input data (characteristics of the community, the WWTP and the receiving media) it provides offline output data (alternatives

WWTP designs and all types of WWTP-related knowledge).

### 3.4.2. Overview and justification of the model selected

In this section a concise overview of the proposed conceptual design method for WWTPs is given.This methodological approach is specially aimed at handling the complexity of dealing with huge amount of information and multiple objectives. It is obvious that a good conceptual design method should include elements of both qualitative and the numerical knowledge-based approaches in a sensible manner. In view of the combinatorial problem emerging from the systematic generation of conceptual design alternatives, the generation step has to be broken down in several subproblems. The chosen method was a knowledge-based system (**3.5.2. Knowledge-based System**) that showed clear advantages for the perfect combination of both the hierarchical decision process (enabling the systematic alternatives generation), and the rule based systems (decision trees). This last one presented clear benefits for the pre-screening of alternatives as can act as an efficient filter (**3.5.4 Complementary decision tree model**). The numerical approach, on the other hand, is well suited for the decision process when only a few alternatives remain. Thus, the proposed method uses the hierarchical approach (**3.5.1 Hierarchichal Approach**) and a structural network model (**3.5.3 Structural Network model**) method for the generation of alternatives while a recursive evaluation method and a multi-criteria is used for their evaluation (**Section 3.5.5** and **Section 3.5.6**).

Therefore, among the numerical, statistical and AI models, was the aforementioned Knowledge-Based System combined with other analytical methods the one selected as an appropriate model to represent and handle the data and information required for the NOVEDAR_EDSS objectives.

The complexity involving the requirements of the EDSS implied the implementation of the following analytical methodologies to manage the different KBs that compose our system. The conceptual design method proposed in this thesis is therefore structured in the following analytical methodologies:

a) *The Hierarchichal Approach (Section 3.5.1.)*

b) *Knowledge-based System (Section 3.5.2)*

c) *The Structural Network model (Section 3.5.3)*

d) *Complementary decision tree model (Section 3.5.4)* *e) Data Processing Module (DPM) and Recursive evaluation (Section 3.5.5)*

*f) Multi-Criteria Decision Analysis (MCDA) (Section 3.5.6)*

***a) The Hierarchichal Approach was selected because:***

One of the main advantages of using this approach is the reduction of design problem. One of the main contributions of the hierarchical approach in the NOVEDAR_EDSS is the design support during the systematic generation of WWTP alternatives and the proper management of the relevant amount of knowledge required in each step of the decision-making process. The approach to generated process flow diagrams proposed in this EDSS is a typical example of a divide-and-conquer type of strategy. The general principle consist in sub-dividing a complex problem into a number of sub-problems requiring abstraction and the consideration of the relationships amongst the sub-problems. A number of controlled assumptions can be listed in favor of the screening part with respect to time savings. It is beneficial that at Upper levels exists a screening method that can be done in a relatively short period time-frame without having to go on the specifics of each technology. Detailed information is only used at advanced design stages, when the decision maker is sure that only a reduced set of alternatives is worth to analyze. Although there is a fair chance that some aspects of the master problem will be lost employing this procedure, the reduced complexity in each problem facilitates the search for good and partial solutions. In the proposed approach, the sub-problems are dealt as elements for the defined levels of abstraction that contain a specific part of the information of the master problems concerning the whole process flow diagram.

***b) The Knowledge-based system was selected from the AI models because:***

Knowledge-based systems (KBS) are artificial intelligent tools working to provide intelligent decisions with justification. The acquired knowledge is represented using various knowledge representation techniques as matrices, rules, networks ... .The basic advantages offered by such system are documentation of knowledge, intelligent decision support, self learning (not applied in our case), reasoning and explanation.

Knowledge-Based Systems (KBS) goes beyond the decision support to involve the expert system into the decision making framework. Expert Systems (ES) have been the tools and techniques perfected by artificial intelligence (AI) researchers to deduce decisions based on codification of knowledge. The codification of knowledge uses the principles of knowledge.

The huge amount of knowledge from different nature required in this project, from qualitative to mathematical expressions, and from easy 6 objects combinations to thousands of them (network model), also the required specifications for thousands of technologies (even, placed in a hierarchichal fashion),the complete implementation of specific methodologies, the calculations rules, ... , converts the KBS in a promising option to organize and manage all the project information within a single system.

***c) The Structural Network model was selected from the AI models because:***

The number of technologies that we have identified within the WWTP flow diagram t is up to 250 (Table 3.2). Moreover, taking into account that all those technologies can be combined in different ways depending on the pre-defined objectives has been calculated that we could obtain more than, approximately, 120.000.000 possible WWTP configurations alternatives. It means that in the conceptual design process approximately the same number of decisions should ºbe taken into consideration by the designer in order to explore the entire response surface of possible alternatives.

An adapted network structure was found as the most suitable method for the automation and generation of WWTP alternatives. The size of the space of possible alternatives might result in a large portion of the response space left unexplored. Moreover, the existing interactions among these technologies, makes difficult to establish compatibilities and relations amongst the units comprising the flow diagram. Therefore, this innovative systematic approach enables the building of a network structure for each type of interaction. The generated directed network structure can be expressed as a response surface of WWTP alternatives of interleaved interactions and treatment technologies in a functional order fashion. Therefore, the single network model can manage all the technologies interactions information and build a suitable milieu in the form of a network.

***d) A complementary decision tree system was selected from the AI models because:***

Decision Trees are included in the domain of Rule Based Systems (RBSs) and are relatively simple computer programs designed to imitate the reasoning process and knowledge of experts in solving problems in a particular domain. Therefore, the NOVEDAR_EDSS should take advantage of this methodology in order to provide solutions in all those situations when rules by experts can be easly created, and implemented in the form of decision trees, rather than look for the almost the same results by mathematical equations or models. The simplification of the decisions using this methodology enables that in specific, or critical, cases only suitable and successful solutions (provided by the expert experience) are selected, and, moreover, allow the time saving avoiding the consideration of non-viable PFDs by multicriteria evaluation. For the integration of this methodology the program uses the domain knowledge coded by means of IF-THEN rules and a specified control strategy to arrive at solutions (Turban, 1992; and Krishnamoorthy and Rajeev, 1996; Turon 2005).

***e and f) Data Processing Module (DPM), Recursive evaluation, and Multi-Criteria Decision Analysis (MCDA) were selected because:***

The Data Processing Module (DPM) or inference engine is the brain of the EDSS. The DPM enables the saving and knowledge flow through the EDSS and makes it works properly. This component is essentially a computer program that provides the concrete methodologies for reasoning about the information in the blackboard (area of working memory set aside for the description of the current problem), and for formulating conclusions.

The implementation of the recursive evaluation analytical methods as complementary methodologies allows the integrated assessment and detailed evaluation of all the generated PFDs for any specific scenario (**3.5.5 DPM and Recursive evaluation**). Whereas the Multi-criteria Decision Analysis (MCDA) (**3.5.6 Integrated assessment and Multi-criteria Decision Analysis (MCDA)**) is the responsible to provide objectivety to the final EDSS outputs, at the same time that a transparent, easy-to-use, and usefuful method to the end-user to customize PFDs assessment is set.

## 3.5. Model implementation and integration

The proposed model for the EDSS is a Knowledge-based System based on a hierarchical decision approach (**3.5.1. Hierarchical Approach)** that breaks down a complex design problem into a series of issues easier to analyze and to evaluate. For each one of these issues, three levels of abstraction are defined (units, submeta-units and meta-units) modifying their degree of engineering detail and thus facilitating the decision maker being focused at each design step. The generation of WWTP alternatives is carried out by means of the interaction of two knowledge bases (KBs) (**3.5.2. Knowledge Bases**). The first knowledge base (**3.5.2.1 Specifications Knowledge Bases: S-KBs**) summarizes the main features of the different treatment technologies i.e, removal efficiency, costs, process reliability. The second (**3.5.2.2 Compatibility Knowledge Bases: C-KBs**) contains information about the degree of compatibility amongst the different technologies i.e. high, low, non-compatible ... Both S-KB and C-KB are linked to other data-bases with additional information about legislation and other environmental-related issues (**3.5.2.3. Environmental Knowledge Bases: E-KBs**). These characteristics are described using an integrated modelling approach through mechanistic process equations (collected in S-KBs attached in the thesis folder), economical cost models, expert and bibliographic knowledge. The combination of the wastewater treatment technologies properties (**3.5.2 Knowledge-Based System**), the network structure model (**3.5.3. Directed Network Structure),** decision trees (**3.5.4. Decision Trees**), and the recursive evaluation method (**3.5.5 DPM and Recursive evaluation System**) altogether with the MCDA (**3.5.6 Integrated assessment and Multi-criteria Decision Analysis (MCDA**) allows: I) the synthesis of multiple flow diagrams including different treatment schemes, ii) analyzing these diagrams from environmental, economic, social and technical point of view. Next, a multi-criteria decision method (MCDM) selects the sequence of unit processes that maximizes the degree of satisfaction of the different objectives.

### 3.5.1. Hierarchical Approach

The hierarchical approach has been lately studied as a feasible and robust methodology to handle the inherent complexity, and involved uncertainty, in WWTP designs (Vidal et al., 2002; Flores et al., 2005; Zeng et al., 2007). The hierarchical process is a well-known technique that breaks down the decision-making problem into several levels in a way that they form a hierarchy with unidirectional hierarchical relationships between levels. The top level of a hierarchy is the main goal of the decision problem (Aragonés-Beltran et al., 2009).

The following section describes the methodology that is implemented in the Knowledge-Based System used to develop the EDSS, which combines the hierarchical decision process with the definition of different abstraction levels. The hierarchical decision process transforms the problem of generating wastewater treatment schemes (WWTS) into a set of elements [E] easier to analyze and to evaluate (Douglas, 1988). The different levels of abstraction modifies the quantity of detail during the conceptual design practice allowing the decision maker be focused on a few concepts at each time (Lopez-Arevalo et al., 2007).

In the presented case study, three abstraction levels are defined:

i) Meta-Units [MU= E1,…,Ei,…,EX]

ii) Sub-Meta-Units [sMU= Ei,1,…,Ei,j,…,Ei,Y]

iii) Units [U= Ei,j,1,…,Ei,j,k,…,Ei,j,Z].

Under this procedure, the design problem is tackled following a pre-defined order: from higher to lower level of abstraction. The highest and the lowest level of abstraction are represented by Meta-Units [MU] and Units [U] respectively where the number of elements comprising the Meta [MU], Sub-Meta [sMU] and the Unit [U] level increase ($X < Y < Z$) as the design process progresses because more detailed information about the future flow diagram is necessary.

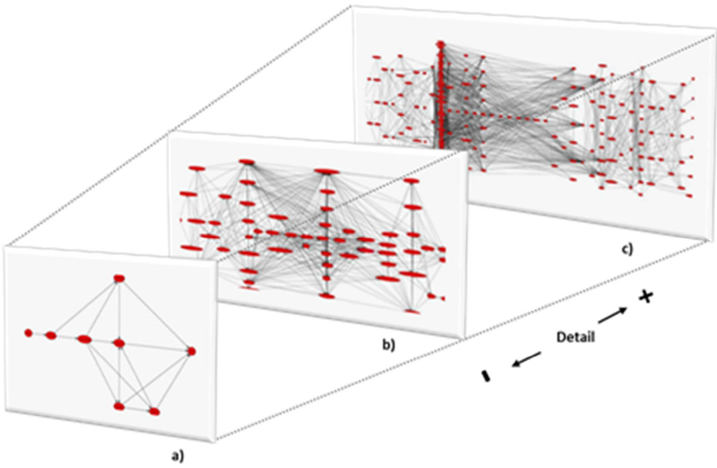



**Figure 3.3.** Level of detail of the design approach in the different abstraction levels.

The encapsulation of the different elements [E] into the Meta [MU], Sub-Meta [sMU] and the Unit [U] level is based on the properties defined by Chittarro et al., (1993) : i) structural i.e. their connectivity, ii) behavioural i.e. how their work, iii) functional i.e. their role within the process and iv) teleological i.e. their objective and justification within the process. Depending of the abstraction level, more detailed (structural and behavioural) or more general (functional and teleological) properties will be used to reason about its aggrupation/aggregation (Figure 3.3). Thus, the number of sub-indexes (1, 2 or 3) included in [E]  will represent the abstraction level (high, medium, low) and the different elements within values of i,j and k will be based on the structural, behavioural, functional and teleological properties.

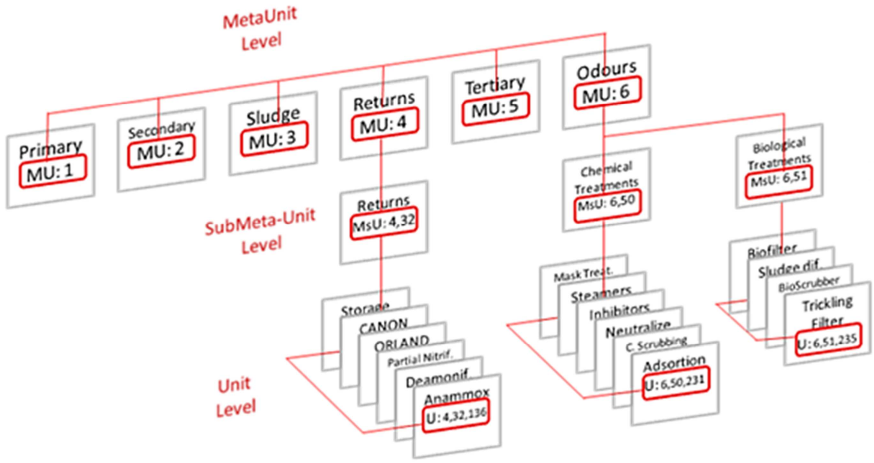



**Figure 3.4.** Graphical representation of the hierarchical design approach.

Figure 3.4. shows a graphical representation of the suggested approach. At the highest abstraction level the elements considered are: primary, secondary, tertiary, sludge, odours and return treatment [MU= E1,…,Ei,…,E6] (X = 6). When additional detail is included the elements comprising the Sub-meta-unit is increased up to 51 (Y = 51). Specifically, when the elements of the Meta-Unit odour treatment (i = 6, E6) are analyzed in detail, two possible Sub-Meta-Units can be found: chemical (j =50; E6,50) and biological (j =51; E6,51) odour treatments. The total number of sub-meta-units for the previously presented meta-units is fouty-nine (Y=51). Finally, at the lowest level of abstraction a list of more than 20 possible alternative (E6,50,226-E6,50,231), including scrubbers, neutralizers, trickling filters, bio-scrubbers amongst others, is browsed. The other example shows the different sub-meta and units comprised dealing within the meta-unit treatment of returns coming from the sludge line (i = 4, E4). The possible range of treatment alternatives moves from Anammox reactors to the storage of the nitrogen rich return during day-time and release at night (E4,36,156; E4,36,162). Again, in the presented example it is possible to see how the level of detail increases from Meta-Unit to Unit level. As well, the reader can appreciate in both cases it was highlighted how at higher levels of abstraction the categories used to differentiate amongst MU and sMU were either functional or teleological e.g. treatment of the liquid phase, treatment of the gaseous phase… while at Unit level the categories were more structural or behavioural e.g. neutralization, adsorption, etc.

One of the main benefits of the proposed approach consists on guiding the decision maker systematically through the different design steps considering the different treatment alternatives. The decision maker is thus forced to include a broad range of possible alternatives. Many times the flow WWTS proposed by the EDSS is almost obvious and in some sort of way expected. However, the advantage of the work proposed in this thesis is the possibility to obtain a not so straightforwardly apparent alternative. This is mainly due to the intensive data-base used to run the EDSS including conventional and innovative treatment technologies. In Figure 3.5 can be seen how the hierarchical approach is coupled within the knowledge-based system and the other EDSS building methodologies.

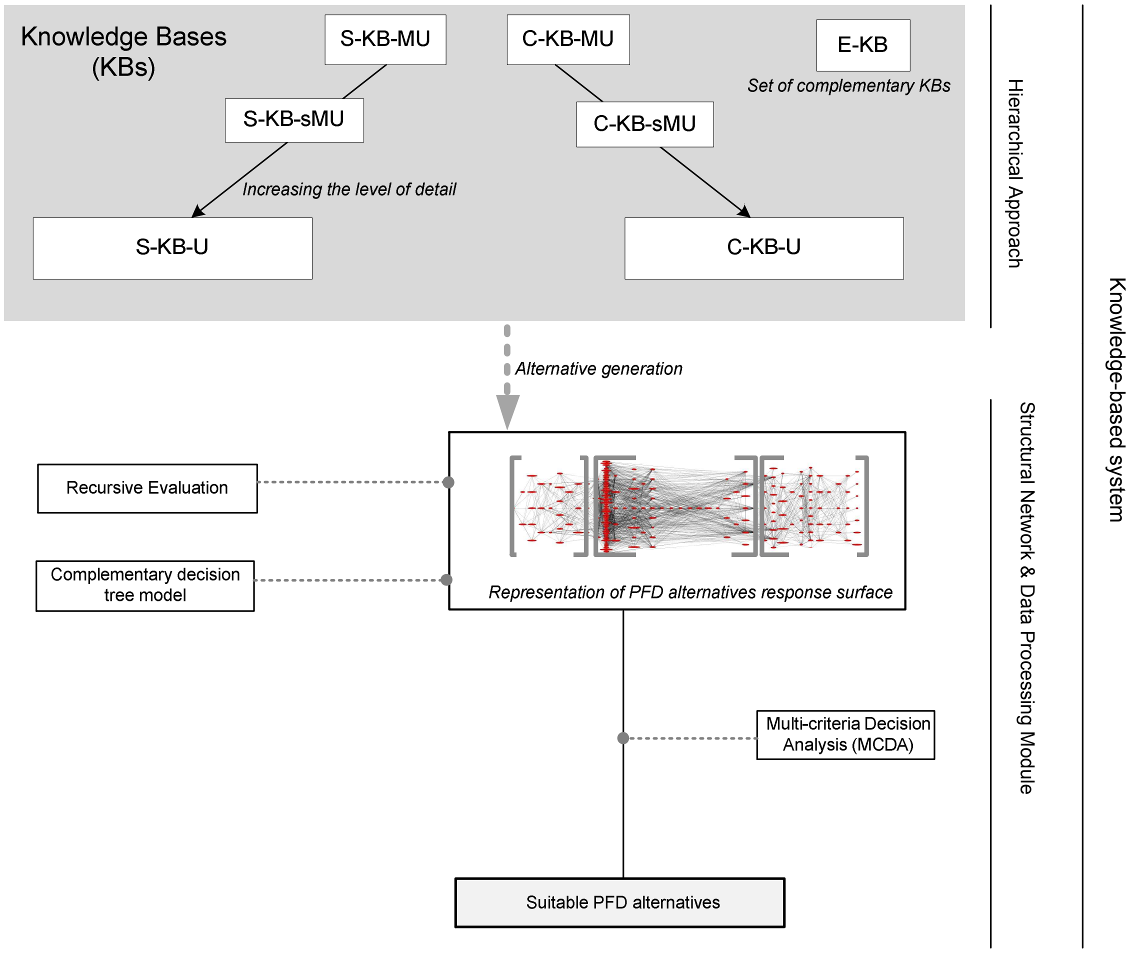



**Figure 3.5.** Schematic representation of the analytical methodologies integrating the NOVEDAR_EDSS.

### 3.5.2. Knowledge-Based System.

The knowledge bases compousing the knowledge-based system provide the essential and necessary knowledge for understanding, formulating and solving problems. Therefore, the set of KBs developed for the different abstraction levels contain information about the compatibility amongst the different elements comprising the different wastewater treatment schemes (C-KB) as well as their environmental, economic, technical or legal specifications and requirements (S-KB and E-KB).

#### *3.5.2.1. Specification Knowledge Base (S-KB)*

A complete characterization of the identified unit processes and clusters of units comprises the S-KBs. This characterization is repeated for the previously defined levels of detail (S-KB-MU, S-KB-sMU and S-KB-U). At the highest level of detail (i.e., the lowest level of abstraction), the S-KBu, 288 unit processes are thoroughly characterized.

More than 20 factors should be considered when selecting a treatment process and designing a treatment train (Metcalf and Eddy, 2003; MWH, 2005). Moreover, most methodologies consider only the major technical and economic factors associated with the selection of a treatment process, such as contaminant removal efficiency and capital cost (Hamouda et al., 2009). Nevertheless, the approach proposed here considers more than 88 different factors. This higher number of factors facilitates an integrated assessment that considers technical, social, political, economic and legislative issues. Furthermore, this high number of factors also enables the use of key indicators and analytical tools, including CBA, LCA, and MCDA.
Therefore, the selected wide range of factors (88) covering five main topics provides the knowledge required for the conceptual design of the PFD. For each technological process or unit, the following information is assembled:

- **Influent:** Parameters that define the incoming water quality. A rank with the minimum and maximum value for each of the parameter is provided.

| Parameter | Units |
|---|---|
| Volumetric Loading | ***kg BOD/m$^3$·day*** |
| Maximmun BOD concentration | ***mg/L*** |
| Inhabitants | ***p.e.*** |
| Flowrate | ***m$^3$/day*** |
| Flowrate variation | ***m$^3$/day*** |
| Total Suspended Solids (TSS) | ***mg/L*** |
| BOD:N ratio | ***No Units*** |
| Total Nitrogen | ***mg/L*** |
| Total Amonium | ***mg/L*** |
| Total Phosphorous | ***mg/L*** |
| Pathogenic Load (specific techs.) | ***fecal coliform/100 ml*** |
| Emergent contaminants | ***mg/L*** |
| Temperature | ***ºC*** |
| Conductivity | ***uS/cm*** |
| Recommended Scenario | ***Selec. from given options*** |

- **Effluent:** Expected water quality if the technology is implemented. This category involves amongst other process efficiencies, pollutant removal capabilities ... The detailed parameters are the following table.

| Parameter | Units |
|---|---|
| Effluent BOD | ***mg/L*** |
| Effluent COD | ***mg/L*** |
| SRT | ***days*** |
| Hydraulic Retention Time | ***hours*** |
| Recirculation/Return Activated Sludge | ***% of influent*** |
| Effluent turbidity | ***NTU*** |
| MLSS (Mixed Liquor Suspended Solids; g/L) | ***g/L*** |
| TSS removal | ***mg/L*** |
| Nitrogen emoval | ***mg/L*** |
| Amonium removal | ***mg/L*** |
| Phosphorous removal | ***mg/L*** |
| Inorganic chemical species | ***mg/L*** |
| | |
| **Pathogenic load removal** | |
| Parasitic Nematodes or Roundworms(helminth) | ***egg/ 10 L*** |
| *Taenia saginata* () (helminth) | ***egg/L*** |
| *Taenia solium* () (helminth) | ***egg/L*** |
| *Escherichia coli* () (enteric bacteria) | ***UFC/100mL*** |
| *Salmonella* (enteric bacteria) | ***UFC/100mL*** |
| *Legionella* spp () | ***UFC/L*** |

| | |
|---|---|
| Total Coliforms | ***UFC/L*** |
| Faecal Coliforms | ***UFC/L*** |
| Faecal Streptococcus | ***UFC/L*** |
| *Giardia* (Protozoa) | ***UFC/L*** |
| Virus | ***UFC/L*** |
| | |
| **NOVEDAR_Consolider TARGET COMPOUNDS** | |
| Antibiotics - Sulfamethoxale (SMX) | ***µg/L*** |
| Antibiotics - Trimethoprim (TMP) | ***µg/L*** |
| Antibiotics - Erythromycin (ERY) | ***µg/L*** |
| Antibiotics - Roxithromycin (ROX) | ***µg/L*** |
| Anti-depressants - Citalopram (CTL) | ***µg/L*** |
| Anti-depressants - Fluoxetine (FLX) | ***µg/L*** |
| Anti-depressants - Diclofenac (DCF) | ***µg/L*** |
| Anti-inflammatory - Naproxen (NPX) | ***µg/L*** |
| Anti-inflammatory - Ibuprofen (IBP) | ***µg/L*** |
| Tranquilizer - Diazepam (DZP) | ***µg/L*** |
| Anti-epileptic - Carbamazepine (CBZ) | ***µg/L*** |
| Anti-epileptic - Estrone (E1) | ***µg/L*** |
| Hormones - 17β-Estradiol (E2) | ***µg/L*** |
| Hormones - 17α-Ethinylestradiol (EE2) | ***µg/L*** |
| Contrast media - Iopromide (IPM) | ***µg/L*** |
| Contrast media - Celestolide (ADBI) | ***µg/L*** |
| Fragances - Tonalide (AHTN) | ***µg/L*** |
| Fragances - Galaxolide (HHCB) | ***µg/L*** |

- **Impacts/sub-products:** Possible environmental effects that the suggested technology can generate.

| Parameter | Units |
|---|---|
| **Related to Life Cycle Assessment** | |
| Electricity use | **KWh** |
| Sodium acetate dosing | **kg NaOAc** |
| FeCl3 40% dosing | **kg $FeCl_3$** |
| Polyelectrolyte | **kg poly** |
| Infrastructure | **$m^3$ influent treated** |
| Nitrogen | **kg N** |
| Phosphorous | **kg P** |
| Liquid waste | **kg/year** |
| **Related to Sludge Production** | |
| Sludge Production (First calc. Method) | **$m^3$ Sludge. Day-1** |
| Sludge Production (Second calc. Method) | **Dry solids, kg/103 $m^3$** |
| **Related to GHG emissions** | |
| VOCs emission | **kg $CO_2$ /year** |
| Gas release - $CO_2$ (Kg) | **kg $CO_2$ /year** |

| | |
|---|---|
| Gas release ($NH_3$) | **kg $CO_2$ /year** |
| Gas release ($N_2O$) | **kg $CO_2$ /year** |
| **Related to social perception** | |
| Odours potential | **Qualitative** |
| Noises potential | **Qualitative** |
| Visual impact | **Qualitative** |

- **Operation:** Expected process performance. This category involves maintenance frequency, potentiality of developing problems, process stability

| Parameter | Units |
|---|---|
| **Operation simplicity** | ***Qualitative rank value*** |
| **Control over the process** | ***Qualitative rank value*** |
| **Flexibility** | ***Qualitative rank value*** |
| **Reliability** | ***Qualitative rank value*** |
| **Space requirements** | ***Qualitative rank value*** |
| **Compatibility degree** | ***Qualitative rank value*** |
| **Maintenance frequency** | ***Qualitative rank value*** |
| **Potentiality of developing problems** | ***Qualitative rank value*** |
| **Process stability** | ***Qualitative rank value*** |
| **Innovation degree** | ***Qualitative rank value*** |

- **Costs**: Quantification of the capital (CAPEX) and the operating (OPEX) expenditures. This category involves estimations about construction costs, investment, aeration energy, use of chemicals

| Parameter | Units |
|---|---|
| **Maintenance** | *M€/year* |
| **Energy Use** | *€* |
| *Total Cost for Air Required* | *€* |
| **Operation and Manitenance cost** | *M€/year* |
| **Investment** | *M€* |

The main difference amongst S-KBMU, S-KBsMU and S-KBU is the quantity of detail. Thus, at higher levels of abstraction (S-KB-MU and S-KB-sMU), knowledge bases are useful to discriminate/screen the alternatives that not satisfy the treatment requirements or decision makers expectations (Figure 3.6). On the other hand, when one moves to the lower abstraction (S-KB-U), the quantity of detail increases substantially and the contained information is used for posterior evaluation.

A conceptual representation of the knowledge assembled in the S-KB is shown in Table 3.3. In this example, four different technologies are partially described according to the influent, effluent, economic costs, sub-products and operation categories. Additional categories are also shown.

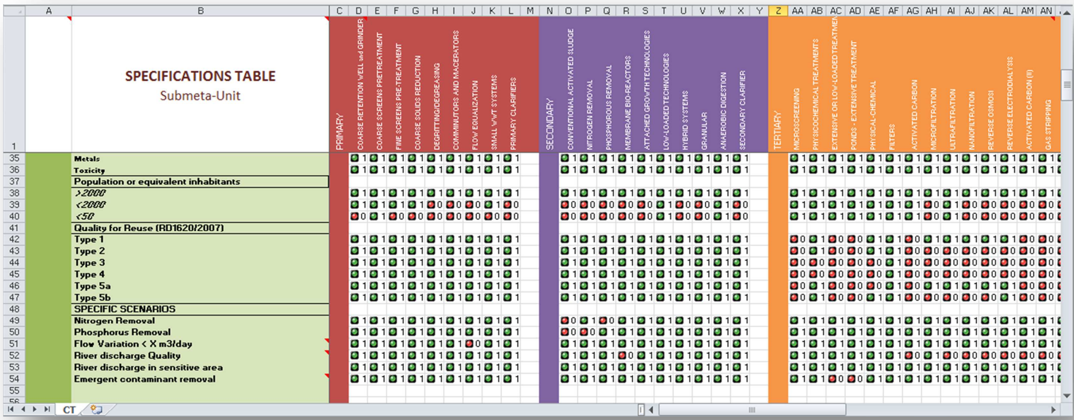



**Figure 3.6.** shows a table summarizing the content of S-KB for low-loaded treatment technologies at the medium level of abstraction (S-KB-sMU). At this level the KBs are only use to discriminate if some combinations of technologies are suitable to the user requirements.

.

| | Anaerobic pond | Wetland (HSCH) | Trickling Bed | Green Filter |
|---|---|---|---|---|
| | | **Influent** | | |
| **Equivalent Population** | Rang: 150-1.500 p.e | Rang:25 -1.000 p.e. | Rang:200-1.200 p.e. | Rang: < 300 p.e. |
| **Hydraulic loading** | 0,01 - 0,08 $m^3$ / $m^2$ · day | 0,015 - 0,06 $m^3$ / $m^2$ · day | 0,01-0,3 $m^3$ / $m^2$ · dday | 0,02 – 0,005 $m^3$ / $m^2$ · any |
| | | **Effluent** | | |
| **Removal Efficiencies DBO** | 50-85 % | 80-90 % | 55-95 % | 90-99 |
| **Removal Efficiencies Nt** | 10-20 % | 30-70 % | 55-85 % | 65-98 |
| **…** | … | … | … | … |
| | | **Costs** | | |
| **Construction Costs** | $y = 4617{,}x^{-0{,}43}$ $R^2 = 0{,}912$ | $y = 3292{,}x^{-0{,}32}$ $R^2 = 0{,}984$ | $y = 1642{,}x^{-0{,}22}$ $R^2 = 0{,}977$ | $y = 8966{,}x^{-0{,}45}$ $R^2 = 0{,}959$ |
| **Operation Costs** | $y = 136{,}1x^{-0{,}38}$ $R^2 = 0{,}951$ | $y = 211{,}5x^{-0{,}40}$ $R^2 = 0{,}945$ | $y = 258{,}6x^{-0{,}41}$ $R^2 = 0{,}942$ | $y = 15543x^{-1{,}32}$ $R^2 = 0{,}975$ |
| **Investment** | Low, except in land purchase | Moderate. Focuses on the earthmoving | Moderate. Focuses on the extra waterproofing and transportation of sand | Low, except in land purchase |
| **…** | … | … | … | … |
| | | **Subproducts/Costs** | | |
| **Sub products** | Sludge Vegetation that can develop in the lakes | Vegetation to be collected and digested sludge | No | Crops harvested |
| **Nuisances** | From odors sporadically and mainly in anaerobic lagoons | Odors can occur, but rarely | No | Very rarely can occur odors |
| **…** | … | … | … | … |

| Operation | | | | |
|---|---|---|---|---|
| **Staff specialization level** | Low. Does not require skilled labor | Low. Does not require skilled labor | Low. Does not require skilled labor | Low-Medium. Does not require skilled labor but knowledge of agriculture or gardening are needed |

**Table 3.3.** shows a table summarizing the content of S-KB for low-loaded treatment technologies at the lowest level of abstraction (S-KB-U). In the specific example, four different technologies are described according to the influent, effluent, economic costs, sub-products and operation categories.

The Alternative anaerobic pond (E2,17,99) is the least favoured nitrogen removal process due to its low effluent percentages of removal. On the other hand, it presents the lowest investment costs, expect in land purchase, and it does not require skilled labour. Wetlands and trickling beds (E2,17,85 and E2,13,57, respectively) present similar construction and operation costs. In the first case, the main costs are related to earthmoving; in the second case is extra waterproofing and transportation of sand. In any case, it is not required skilled labour. As can be seen in Table 3.3 both cases present very wide organic carbon and nitrogen removal efficiencies. This fact is attributed to the way the system is operated. Nevertheless, the main differences rely on the range of applicability and the generation of sub-products. One one hand, trickling beds can be applied on a wider range of hydraulic loading conditions. On the other hand, wetland systems vegetation and sludge must be collected and there is a high chance of having odour problems

In the end, the alternative green filter (A2,17,93) presents the best percentages in organic carbon and nitrogen removal and the lowest construction and operation costs, although it can only be satisfactorily applied in very small communities. Together with the trickling filter, this alternative can be constructed close to populated areas due to their lack of odour production. Finally, it must be mentioned that skilled personnel is necessary for its both operation and maintenance to harvest the crops produced.

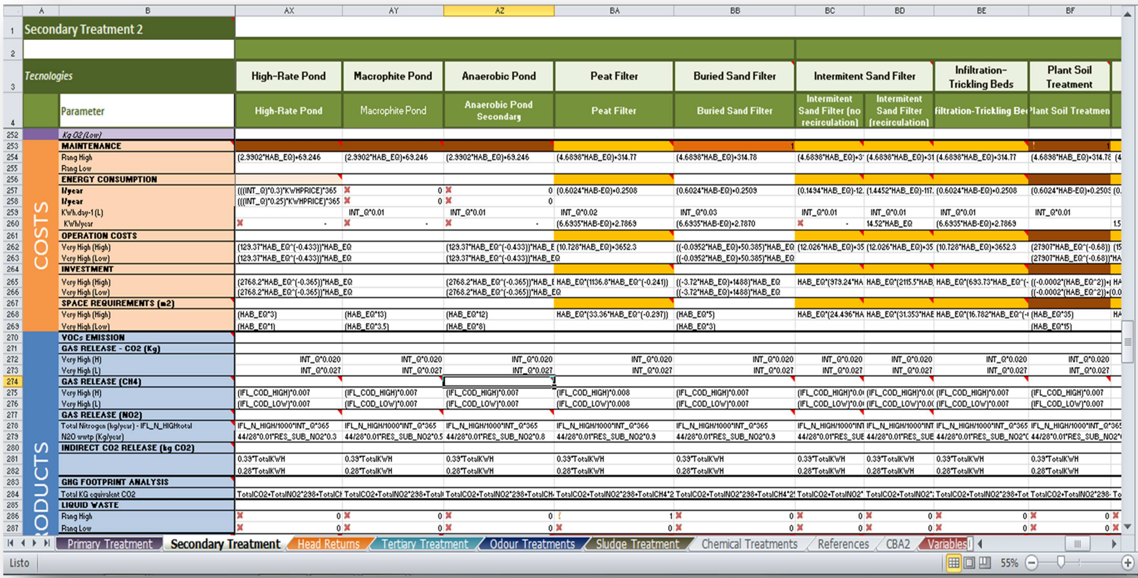



**Figure 3.7.** Shows a real snapshot of the S-KB for low-loaded treatment technologies at the lowest level of abstraction (S-KBU). Further detail and parameters are given in this level. This figure shows the main parameters included in Costs and Subproducts categories.

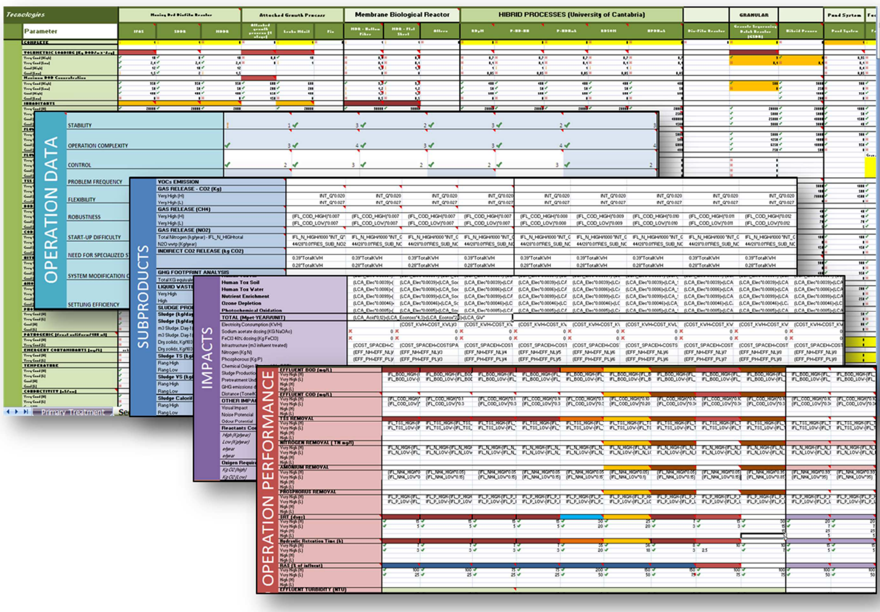



**Figure 3.8.** Snapshots of the specifications knowledge base (S-KB).

### *3.5.2.2. Compatibility Knowledge Base (C-KB)*

The compatibility knowledge bases (C-KB) are comprised of unidirectional tables that establish the type of interaction amongst the units comprising the flow diagram. The C-KB is available at meta-unit (C-KB-MU), sub-meta-units (C-KB-sMU) and units (C-KB-U) level. Therefore, C-KB is composed by three matrixes corresponding to each abstraction level (6x6, C-KBm; 54x54, C-KBsm and 200x200KBu).

Four main types of interactions were identified describing the possible compatibilities. Also, as in the previous case, the different C-KBs have been built by means of literature review and interviews with process engineers and practitioners.

| | EXTENSIVE TREATMENTS | PONDS - EXTENSIVE | PHYSICAL-CHEMICAL | FILTERS | ACTIVATED CARBON | MICROFILTRATION | ULTRAFILTRATION | NANOFILTRATION | REVERSE OSMOSI | ELECTRODIALYSIS |
|---|---|---|---|---|---|---|---|---|---|---|
| EXT. TREATMENTS | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| PONDS – EXTENSIVE T. | 4 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| PHYSICAL-CHEMICAL | 4 | 4 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| FILTERS | 4 | 4 | 4 | | | 0 | 0 | 0 | 0 | 0 |
| ACTIVATED CARBON | 3 | 3 | 4 | 4 | | 0 | 0 | 0 | 0 | 0 |
| MICROFILTRATION | 4 | 4 | 4 | 2 | 0 | | 0 | 0 | 0 | 0 |
| ULTRAFILTRATION | 2 | 2 | 0 | 4 | 4 | 4 | | 0 | 0 | 0 |
| NANOFILTRATION | 0 | 0 | 0 | 4 | 4 | 3 | 4 | | 0 | 0 |
| REVERSE OSMOSI | 0 | 0 | 0 | 4 | 4 | 4 | 4 | 4 | | 0 |
| ELECTRODIALYSIS | 0 | 0 | 4 | 4 | 4 | 3 | 2 | 1 | 0 | |

**Table 3.4.** show the compatibilities assigned to the different sub-metaunits (sMU) at Tertiary (MU3) level. It represents how is the physical/logical relation between sMUs in this specific section (E3, 19-35), considering that the sMUs in the upper row would precede in the WWTP flow sheet the sMU in the vertical column. In the Upper, Medium and Low abstraction level 4 degrees of compatibility are considered (4: High Compatibility; 3: Normal Comp.; 2 Low Comp.; 1: Potential Incompatibility; 0: Incompatibility). For example, for the Pond-Extensive Treatment (sMU3,22) and Microfiltration (sMU3,25) has been assigned a high compatibility (4)

cause as referenced by Metcalf (2004) microfiltration has been used as a replacement for depth filtration as pretreatment step when higher effluent quality is required. Other example, Microfiltration (sMU3,35) has not the highest compatibility degree preceding the Nanofiltration (sMU3,27) as the Ultrafiltration (sMU3,26) is more recommended (Metcalf; 2004). Moreover, it is not recommended to complement Conventional filters: with sand, gravel or synthetic material (sMU3,23) with Activated carbon unit (MU3,24; Metcalf & Eddy, 2004) as their function and performance within the flow diagram are quite similar. In the same table is shown that before a Electro dialysis system (sMU3,29), any Physicochemical, filters and activated carbon units (sMU3,20; sMU3,23; or even, sMU3,30, respectively) can be included. However, neither Extensive treatments (sMU3,22) nor Reverse osmosis (sMU3,28) can be considered (Metcalf & Eddy, 2004).

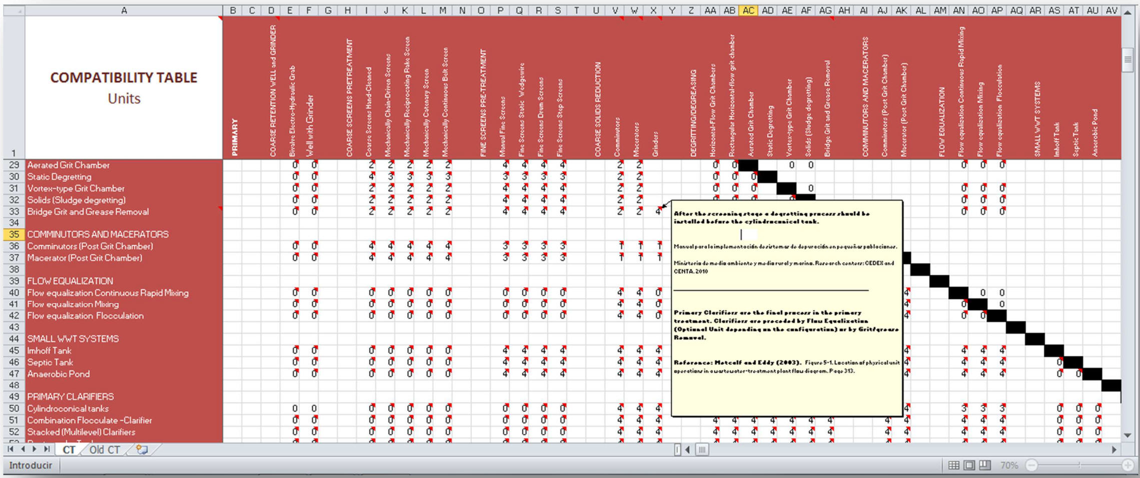



**Figure 3.9.** Shows a real snapshot of the S-KB for low-loaded treatment technologies at the medium lowest level of abstraction (S-KB-sMU). Any compatibility between technologies or units is referenced and any comment about is saved in the form of a comment (Excel Format). The inference engine can extract any comment from the C-KB to show it in the interface.

Thus, when considering the information contained in C-KB it is possible to answer questions such as: Is it possible to include a certain technology X after another technology Y? Could these technologies run together in the same plant? Is it necessary to include a certain technology X if Y is already running? This information is extremely useful because ensures the technical reliability of the generated WWTP alternatives, recommends alternatives that must go together and avoids the inclusion of redundant technologies.

#### *3.5.2.3. Environmental Knowledge Base (E-KB)*

The environmental Knowledge Bases (E-KBs) contain information of different nature, like applicable legislation, information about the environment receiving media, identify limits to accomplish for different operations, databases for the evaluation of global impacts and, even, for calculate environmental externalities. The E-KBs is composed by 1) 3 Matrices, and 2) 5 Knowlegde Bases related to the WWTP domain. Further information can be found at (CD Thesis)

- 1 KB comprising all information about wastewater quality: European Water Framework Directive (Directive 2000/60/EC) and the specific Spanish legislation in the Reuse (Royal decree 160/2007).
- 1 KB comprising all information about biosolid treatment and processes. [In Spanish] *Plan Nacional de Lodos de Depuradoras de Aguas. Residuales 2001-2006 (PNLD)*.
- 1 KB and 1 Matrix containing all aspects related to the implemented methodology of economic assessment.
- 1 KB and 2 Matrix containing all aspects related to the implemented methodology of life cycle assessment.
- 1 KB that embrace or transforms two decision trees into a functional methodology for the selection of specific technologies according the ratio C/N and P/N ratio at the influent.

### 3.5.3. A Structural Network approach for the generation of PFDs

The structural network methodology implemented enable the combination of both typologies of KBs (**3.5.2.1 Specifications and 3.5.2.2 Compatibility** ). The so called structural networks are applied in our system in order to generate suitable process flow diagrams (PFDs). Thus, in the following section the methodology used to automatize the generation of PFDs is detailed.

Firstly, the concept of network can refer to any interconnected group, cluster, or system, which consists of nodes or elements that are connected by links. Nodes may be joined by more than one link, but no node is isolated (Figure 3.10). The concept of a network could be useful in helping us to portray the existent complex relations in the wastewater treatment plants. There are also many examples of networks in transportation, computer science, flow problems, ... When a network is used to show connections from point to point (e.g. WWTP-related technologies) with regard to direction, it involves the use of chains for linear connections along a sequence of points, starting from the first element, or point, and ending with a last point. Detailed examples and applications of networks in decision making are abundantly illustrated (Saaty and Ozdemir, 2005).

A network structure based on expert knowledge, and adapted to the WWTP characteristics, was chosen as the most suitable tool to support the generation of the whole response surface of PFDs. A network structure represents a decision-making problem as network of elements, grouped into clusters. All the elements in the network can be usually related in any possible way. Nevertheless, the proposed network had to adapt to the specific WWTP requirements. Wastewater treatment plants, as many other (bio)chemical process are characterize for an internal order of operation/reaction units. Therefore, using a directed network structure enables the interaction of the existent elements composing the structure but only within the functional order in the WWTP flow diagram.

(a) (b)

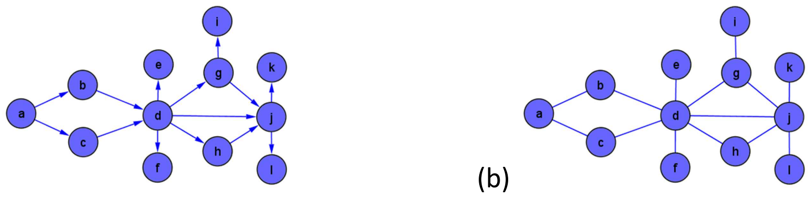



**Figure 3.10.** Example of a directed network (a) and an undirected network (b).

Because of the complex interrelations involved, it may not be easy to classify the elements by levels as in a hierarchy because of the need for feedback and for inner dependence loops, and, thus, a network representation is more appropriate. Once the network structure is constructed the assessment procedure proposed allows the analysis of all the alternatives generated extracting them from the network. Also, using a decision-making method based on the Analytical Network Process (ANP) the evaluation of the different alternatives is possible.

As WWTPs always have the same function expressed in a similar input-output structure (Vidal, 2002) it can be assume that WWTPs flow diagram would remain rather constant. As a result, treatment plant design starts with a relatively established flowsheet structure. In this current study the structure has been summarized in a knowledge base where all WWTP-related technologies identified maintain some type of interaction with all the rest. Firstly, a selection of all the current available technologies in the wastewater market was done, and aprox. 260 WWTP-related technologies within the WWTP flow diagram were used (operational units from pretreatment, primary, secondary, tertiary and sludge treatment, ...). Secondly, compatibilities (physical, functional and teleological relations) between the different technologies (C-KBs) were also considered. In this way, the previous four types of interactions between WWTP-related technologies were taken into account (4: High Compatibility; 3: Normal Comp.; 2 Low Comp.; 1: Potential Incompatibility; 0: Incompatibility) and a network structure was built embracing all these types of interactions possibilities.

Therefore, a logical scheme of all sections in a plant following the C-KBU was established (i.e. Pre-treatment preceding Primary treatment, ...) and implemented to the EDSS. Later on, using the 4 categories of compatibility between units is possible to create a virtual structure encompassing all possible relations and technologies. In fact, a network structure can be also built for each type of compatibility. Thus, the space of possible WWTP alternatives configurations is expressed as an oriented network structure (Figure 3.11) where nodes (WWTP operational units) and edges (influences/interactions between units) compose the structure:

(1) *Nodes.* Within the network structure WWTP technologies are represented as nodes. Nodes in the network structure include the knowledge acquired from different sources about their specifications and their behavioral models. A linkage between the representing technology nodes with an external knowledge base, containing the specific knowledge of each unit, allows the consideration of the properties of each individual node when an analytical method is applied. Furthermore, a Multi-criteria Decision Method (MCDM) can be used to evaluate in an integrated fashion the quantification factors indices evaluating the clustered PFDs.

(2) On the other hand, *edges* representing technology interactions and their connectivity properties can be analyzed in order to obtain several "node centralities" (Bañarés-Alcántara, 2010) i.e. eigen value centrality (a measure based on the largest positive eigenvalue of the network adjacency matrix which, incidentally, is related to the page ranking algorithm used by google). Next, node centralities can be used to measure its relative importance within the network (Freeman, 1978).

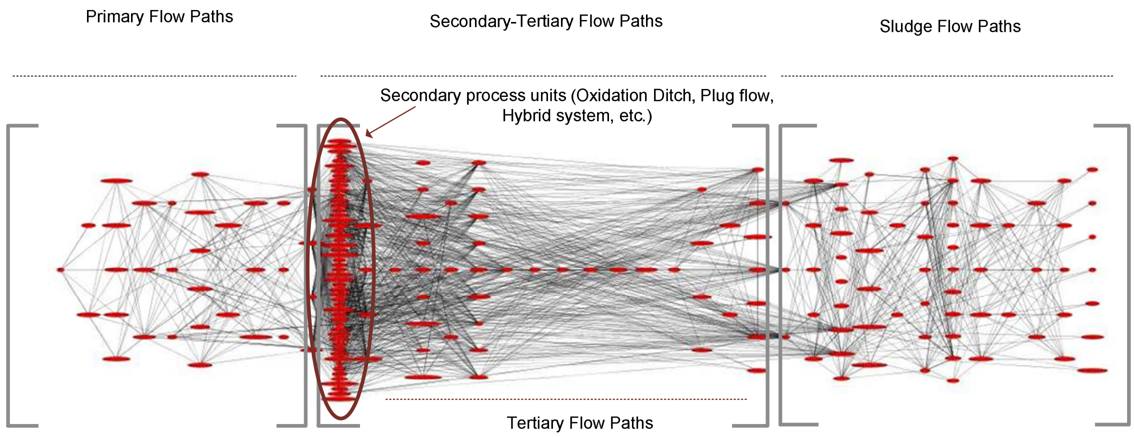



**Figure 3.11.** The Oriented Network Structure built from the compatibility knowledge base (C-Kb) illustrating the main physical relations between process units; Elements/nodes corresponding to the main four parts of the WWTP flow sheet are pointed out.

As previously indicated, each node comprises individual properties belonging to the WWTP technology which they represent. Nodes, also, contain information about specific properties as a node, thus, different types of nodes exist in the designed network in order to enable the flow diagrams generation. A directed network structure involves linear connections along a sequence of points. So, starting-points are needed to start the interleaved chain of elements and interactions. In turn, end-points nodes also exist to cut the chain, forming a possible WWTP flow diagram each time an initial starting-point meets trough a sequence an end-point. Thus, the whole set of existent PFDs is automatically generated if the first set of elements (starting-point nodes) reach the end-point nodes.

Moreover, mimicking the WWTP operational order of the technologies in a plant, the nodes are clustered depending on their function within the treatment process. Many of the technologies present in the network structure, in addition to their specific characteristics (i.e. energy consumption), share the same theoretical function in the plant flow diagram (i.e. sludge drying). Therefore, nodes belonging to identical functional groups have been gathered into clusters. The elements of a cluster can be related to elements of another cluster or to elements of the same cluster (Usual interactions: Incompatibility or complimentarily).

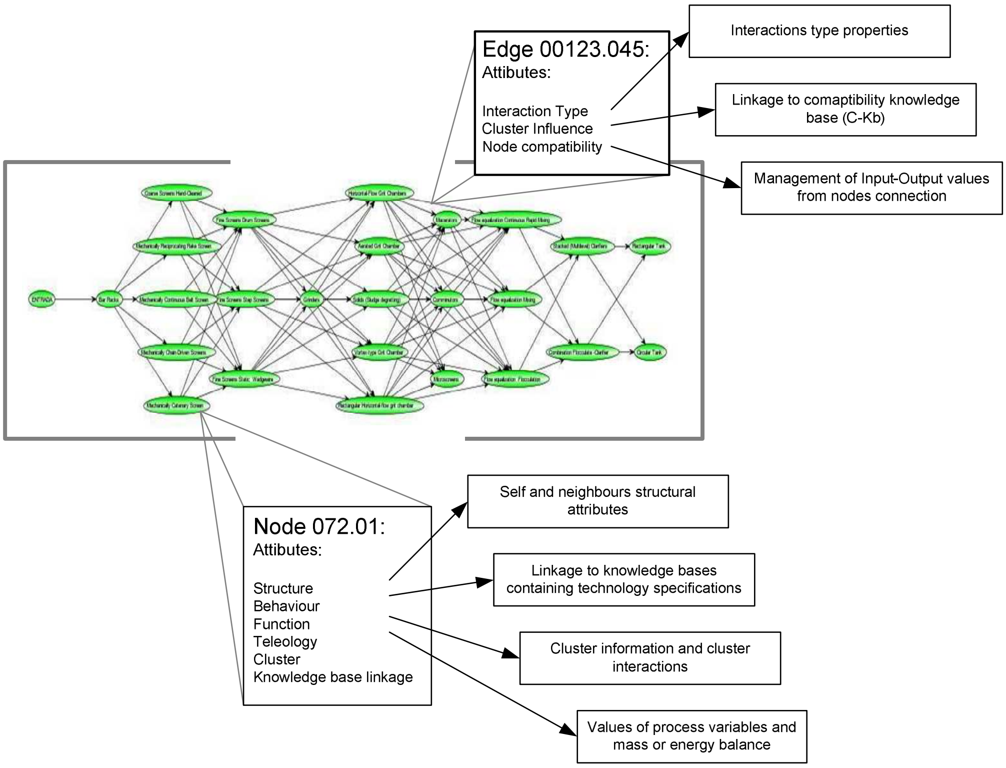



**Figure 3.12.** Encapsulation of knowledge in nodes and edges within the network structure. Nodes within the same vertical edge compose a cluster.

The synthesis of the design problem in a network structure brings the chance to summarize all possible WWTP configurations (PFDs). The represented network in the form of an oriented digraph facilitates the visualization of alternatives options. Nevertheless, the entire wide range of possible combination of elements has to be extracted from the structure in order to carry out the individualized evaluation of every PFD. Encapsulated knowledge in the nodes determines which elements, or specific clusters, can act as end-point of the flow path (Figure 3.12).

Moreover, to face up such amount of information the EDSS is designed to allow the user control the number of generated alternatives by modifying the degree of compatibility between units (selecting WWTP configurations between the 4 different levels of compatibility) and, also, imposing restrictions (penalizing some of the criteria or parameters that can be found on the scenario definition, restrict the search of alternatives to those which are composed of some specific technology, or unit combination, ...).

Once the synthesis of the WWTP process and the alternatives generation step have been applied is of the upmost importance to evaluate the different alternatives in order to rank them and select the most suitable ones from the whole response surface (3.5.5. DPM and Recursive Evaluation). In figure 3.13 the methodological approach is presented:

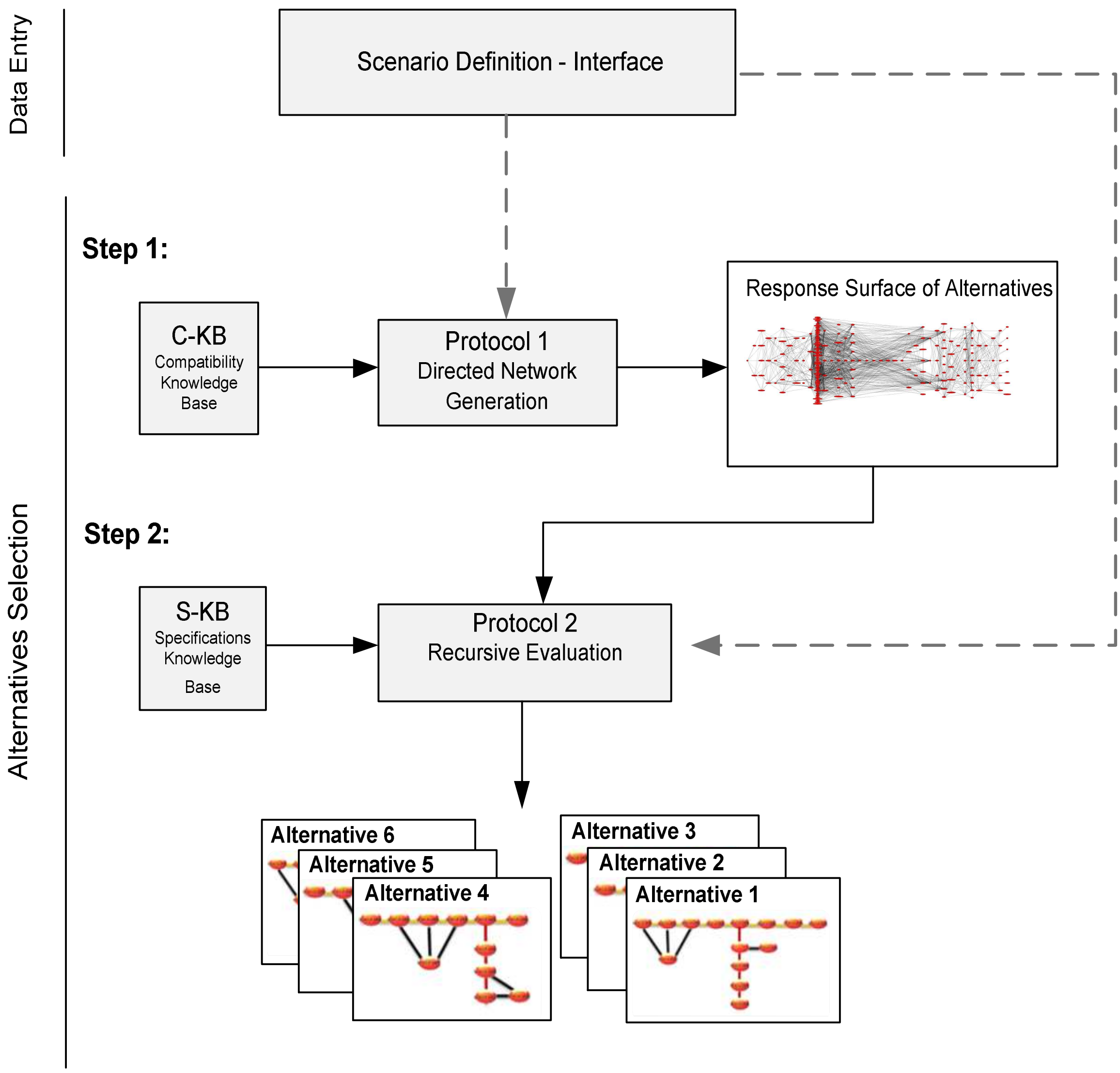



**Figure 3.13.** Decision-making process scheme.

### 3.5.4. Complementary Decision Trees

Two complementary decision trees (DT) to support technology selection for some specifics cases were implemented in the EDSS (see Chapter 7). The information contained in the DTs or in the technologies options represented in each of the DTs branchs can be found in the attached E-KB folder of this manuscript. The two decision trees presented in this thesis are constructed exclusively by expert knowledge and no data mining or inductive methods were required to build them. The decision trees implemented in this thesis are exclusively to improve the technology selection (saving time and computer sources) when the nutrient removal is required, creating expert or optimal solutions to bring to the user convenient options. Using DTs computer sources are saved as the MCDA can be partially avoided by the expert shortcuts which represent the DTs. Moreover, the options provided are more predetermined and the EDSS can provide explanations and more complex solutions thanks to this systematization. The information contained in each branch, or the technologies representing each of the possible choices, can be found in the E-KB folder. Dependending on the solution given (or selected branch) the EDSS would display some of the reasoning that was used to select such specific option.

As said previously, this methodology is specificaly used in the EDSS when rules created by experts can be simplified and converted into decision trees able to provide the results in an easier way than using other more complex analytical methods as the recursive evaluation and the multicriteria themselves (**3.5.5. DPM and recursive evaluation and 3.5.6 Multicriteria Analysis**). This statement does not mean that when this type of rule-based system (RBS) is used the solution is selected exclusively by rules. On the contrary, the set of solutions left, once the RBS is used, are further evaluated and calculated by the recursive evaluation and after that are conviniently ranked using the multicriteria. However, the RBS is extremely useful to provide a quicker screening in those situations where experts (guided by experience) are full convinced that some solutions are not convenient (for more complex interactions that the current scope of the EDSS would reach satisfactorily), and therefore, the use of decision trees led us, when critical situations are found, to convenient and successful combination of technologies.

Decision Trees are part of a knowledge base (Rolston, 1991; Turban, 1992; and Krishnamoorthy and Rajeev, 1996): The knowledge base contains the necessary knowledge for understanding, formulating and solving problems. It includes two basic elements:

- **Facts:** A statement or assertion of verified information about something that represents the initial working memory.

- **Rules:** The rules should encompass all actions to be taken within the scope of a problem but nothing irrelevant.

The decision tree mechanism is based on the comparison of (1) data (input data and intermediate results) stored in the working memory and (2) the IF condition part of rules stored in the knowledge base. The inference engine or DPM allows the triggering of those rules whose conditions are satisfied. When a rule is fired, any actions specified in its THEN clause are carried out. These actions can provide an intermediate result which can trigger another rule or apply for more input data from the user. This loop of firing rules and performing actions continues until one of these two conditions is met: (1) there are no more rules whose conditions are satisfied or (2) a rule is fired whose action specifies the program should terminate.

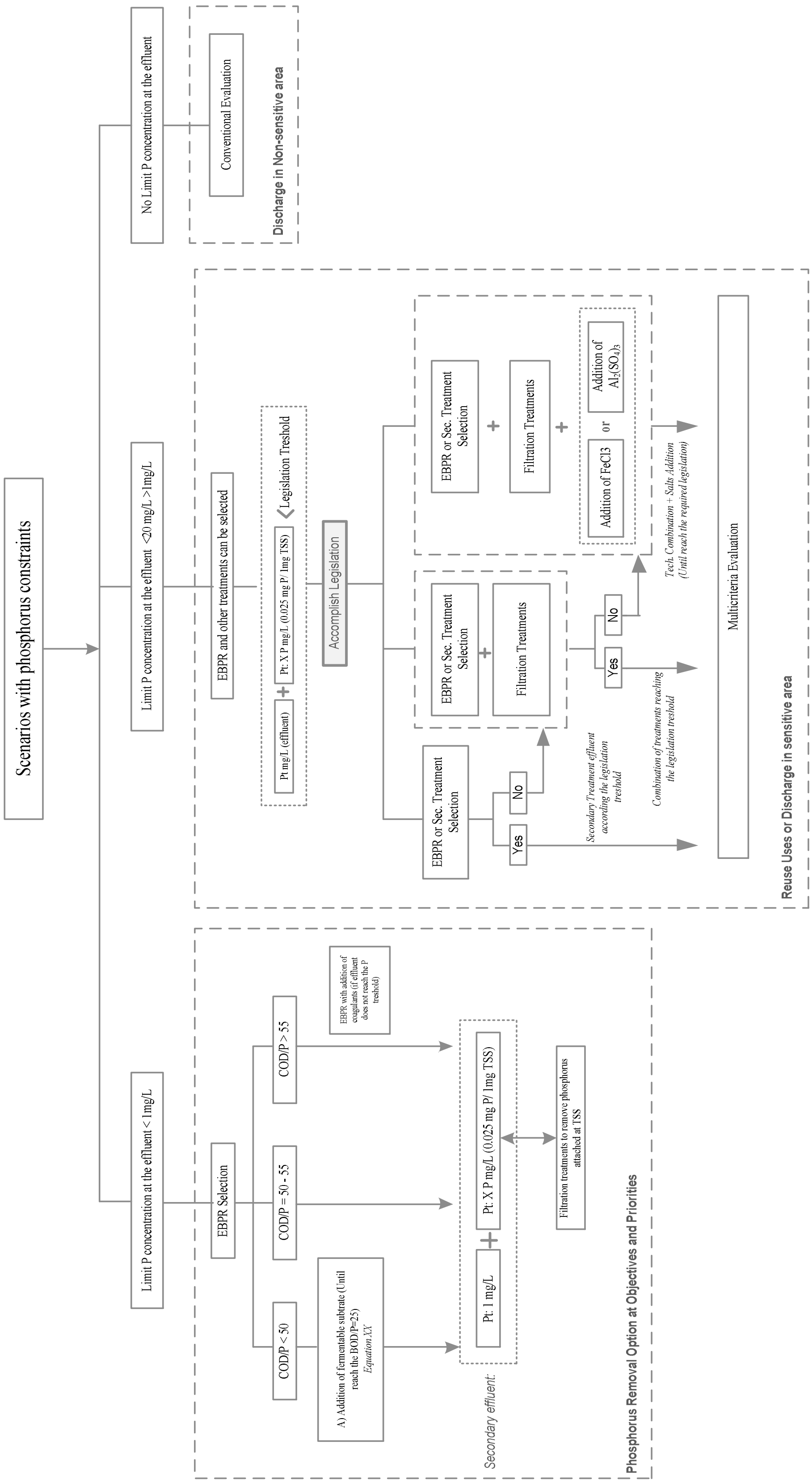



**Figure 3.14.** Decision tree implemented into the EDSS reasoning process.

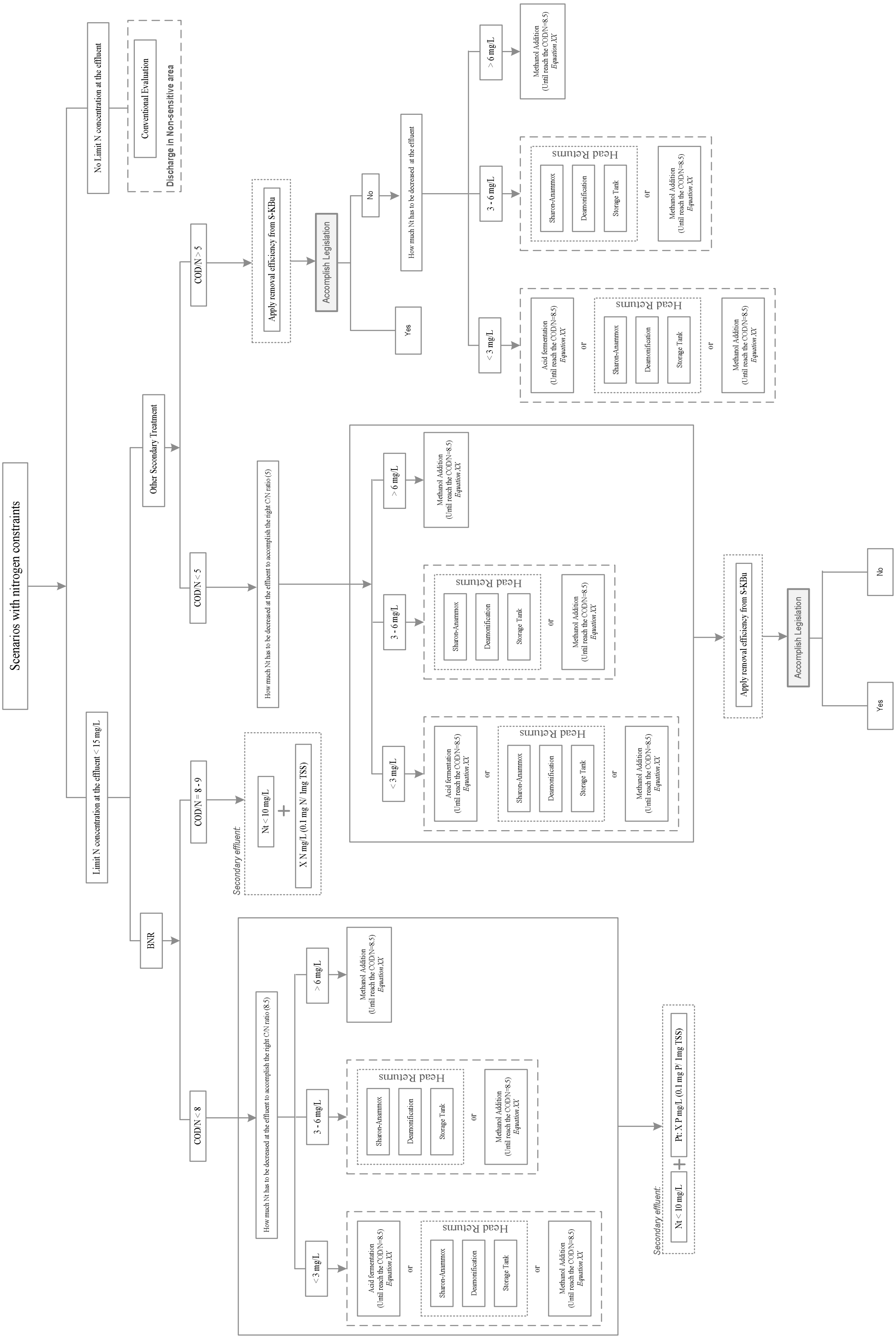


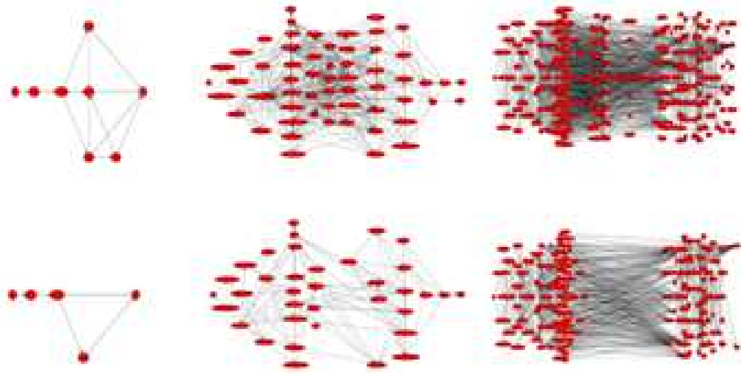

**Figure 3.15.** Decision trees implemented into the EDSS reasoning process for the C/N ratio.

### 3.5.5. DPM and Recursive Evaluation

The data processing module (DPM) is the core of the proposed EDSS. The DPM extracts the collected knowledge from the previously presented KBs (S-KB, C-KB and F-KB) and using this information generates the different WWTP alternatives according to the treatment requirements and the decision maker desires. The main functionalities of the DPM module are i) suggesting WWTP alternatives taking into account the compatibility amongst the integrating treatment technologies, ii) screening the WWTP solutions that not satisfactorily accomplish the degree of satisfaction of the considered objectives and finally iii) propagating the data from the scenario definition main characteristics of the treatment technologies through the generated WWTS for subsequent evaluation.

The information in the C-KB is extracted by the DPM to determine the PFDs compatibility at MU, SMU and U level. Such information is represented as the previously detailed structure in the form of a network. DPM also makes use of S-KB in a different way depending of the level of abstraction. A pre-screening stage is used to simplify the evaluation of multiple alternatives (Loetscher and Keller, 2002). This stage is only used for the MU and MsU levels. Therefore, at high and medium level, S-KB is used to screen the alternatives that do not satisfy either the treatment requirements or the decision maker desires. In this way, it is avoided to evaluate in detail, alternatives that at higher levels of abstractions could resulted to be unfeasible. As an example, Figure 3.16 shows the advantages of using S-KB at the most abstract design level. The first plot (left) represent the possible PFDs resulting from C-KB. When not possible restrictions are applied the number of sub-meta-units is 381.Nevertheless, when the initial design conditions justify the exclusion of treatment of returns, odours and tertiary, the number of sub-meta-units is reduced to 116. Additional screening process can be done from sub-meta-unit to unit, decreasing even more the number of alternatives. In order to do that, it is necessary to go ahead through the design process. Hence, more information about the future plant is required in order to decrease or remove non-suitable alternatives.

Once the compatible PFDs have been created, feasible solutions that meet the user overall degree of satisfaction has to be selected. The previously generated Directed Network Structure is used as a functional structure for the transfer of information. Next phase includes the screening, propagation and evaluation of the entire set of PFD alternatives described by the structural network. The flow paths (edges) between units, which are obtained from the C-KBs, can be used as functional connections to send and save information between nodes. The structural network, then, becomes a functional system capable of conducting an integrated assessment of treatment trains.



| | | Meta-Unit (MU) | SubMeta-Unit (sMU) | Unit (U) |
|---|---|---|---|---|
| Edges | Before Screening | 15 | 381 | 1694 |
| | After screening | 5 | 116 | 1093 |
| Nodes | Before Screening | 8 | 58 | 243 |
| | After screening | 5 | 37 | 173 |

**Figure 3.16.** Screening reduction example through the three abstraction levels once the DPM and the recursive evaluation assess the PFDs response surface

The implementation of a data processing module (DPM) complementary to the network structure facilitates the proper management of the required operations for the evaluation of PFDs. With a DPM, the network structure has the capacity to transfer, transform and manage different types of data. Moreover, a DPM detects the diagrams clustered in the network and extracts them as single PFDs. After this extraction, the multiple technological combinations can be evaluated. Evaluation of each possible diagram relies on the data introduced by the user in the data entry step. These data, including influent characteristics, desired effluent parameters and various objectives, must be specified prior to recursive evaluation. Using information on local circumstances and water quality collected during the scenario definition, this screening stage identifies and discards inappropriate PFD alternatives that do not satisfy user requirements.

Next, the propagation step transfers information through the nodes. During propagation, data from the data entry step are transferred through the combinations of nodes that represent any feasible PFD. This procedure is called recursive evaluation (Fig. 3.17). Scenario-specific data are modified and used by equations, expressions and other data encompassed in the 88 factors or parameters that define the nodes (technologies) of the diagrams. As said previously, all these factors are linked to the S-KBs. The information output generated by each node after being exposed to the scenario-specific data is saved. This process is repeated for all nodes until an end node terminates the propagation. Finally, a complete evaluation of the different combinations of nodes (PFDs) clustered in the response surface is produced. All PFDs that after the propagation step results do not reach any of the specified user requirements is being directly removed (i.e. PFDs that do not meet the minimum concentration of phosphorous by legislation when discharging in a sensitive area).

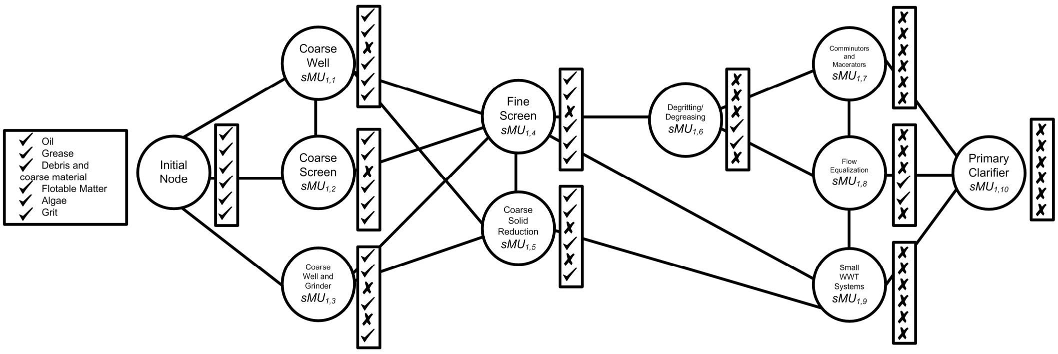



**Figure 3.17.** Conceptual and simplified representation of the data propagation through the Directed Network Structure. The data introduced for the scenario definition (i.e. initial BOD, pathogenic load, ...) can be propagated through the structure composed by nodes and edges. Using this structure is possible to carry out the so called recursive evaluation, allowing the evaluation of all the possible diagrams contained within the structure.

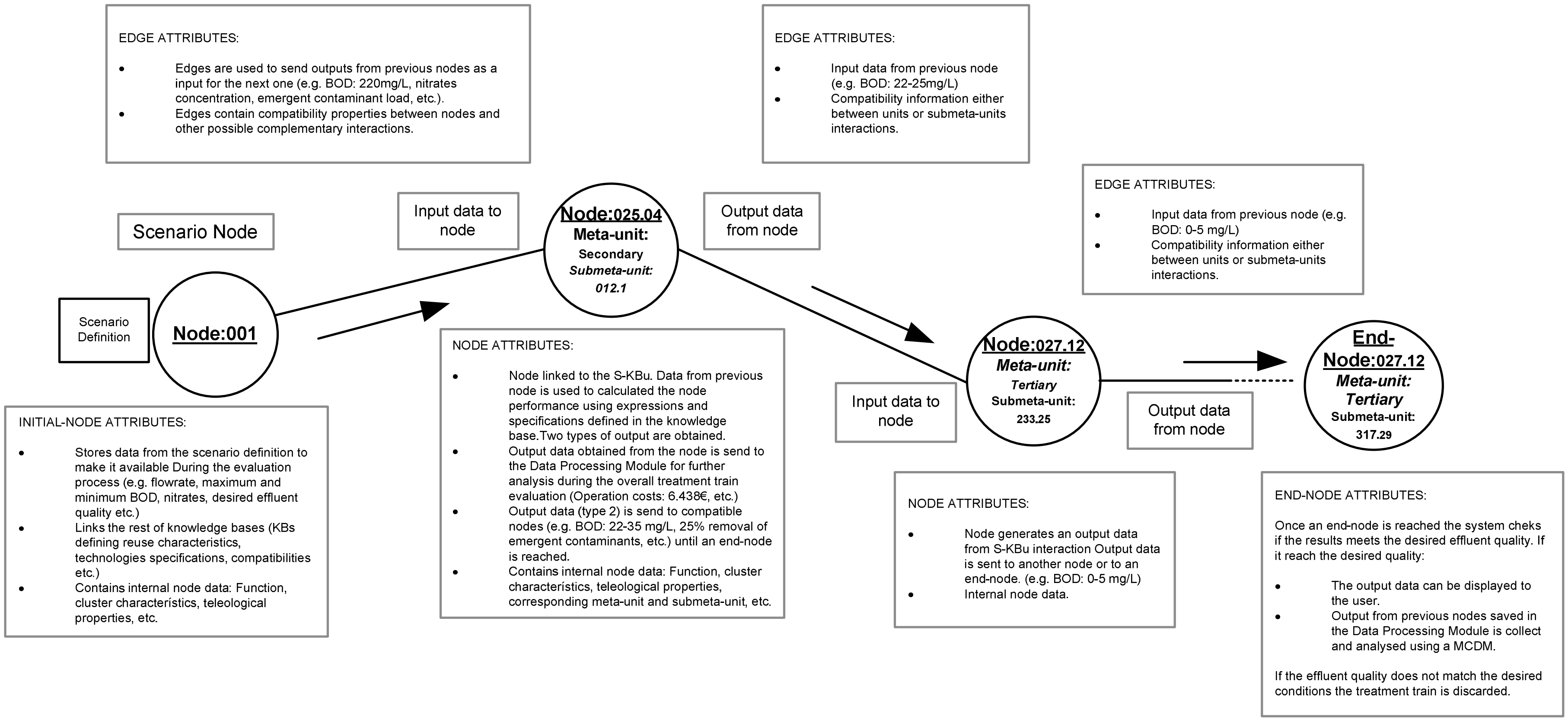



**Figure 3.18.** Schematic representation of the recursive evaluation process. Data flow and process functions within the Directed Network Structure using the data processing module.

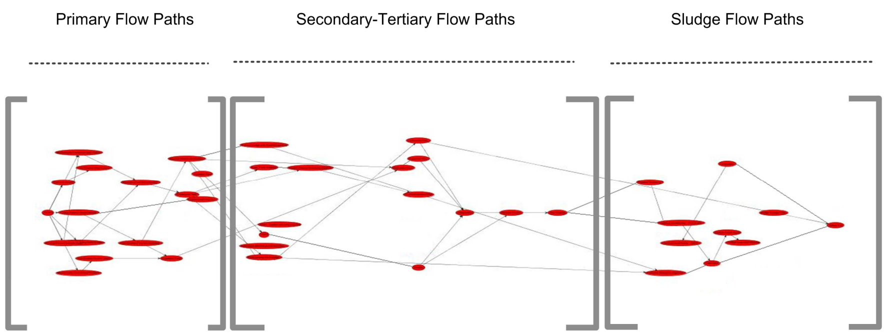



**Figure 3.19.** Example of treatment trains selected from the Directed Network Structure after the screening of options.

### 3.5.6. Multi-criteria Decision Analysis (MCDA)

The selection of an ideal wastewater treatment alternative is associated with distinct multi-objective and hierarchy characteristics. In this study, the selection of the most suitable alternative option is considered as a multi-criteria decision problem taking into account the environmental, social and economic and a technical trade-off analysis. The proposed procedure to evaluate the previously generated *n*-alternatives, using the Knowledge-based system, combines the hierarchy process with *multicriteria decision* analysis. During the alternative generation process a large number of alternatives have been created while many of them had been ruled out due to incompatibilities detected. The remaining alternatives compose the response surface for a specific context. The selected methodology allows the exploration of the whole response surface in order to find the most suited WWTP alternative.

Deterministic MCDA is the traditional decision analysis method used to determine the total values of the alternatives and hence the ranking of each alternative for each set of actor's criterion weights. Value or Utility Multicriteria Theory decomposed the problem in different criteria, evaluating each parameter using value functions. Then, a weight is assigned to every criterion, and finally, some added models apply the results of each criterion with respect to an alternative. The alternative with highest total value is the problem solution. The program currently supports the value focused technique Weighted Sum Method (WSM), which are utilized to determine the total value of each alternative for the assigned input parameters. The WSM involves calculating and appraisal score for each alternative by multiplying each criterion by its appropriate creiteria weight, followed by summing the weighted scores for all criteria.

According to Vidal et al. 2003, there are six main steps to follow in order to apply the Value Multicriteria Theory. Therefore, taking into account our project characteristics, the following approach and its main steps are shown:

**(a) Identification of the issue to be solved.** The issue addressed by the EDSS is the accomplishment of the overall objectives according to the several criteria used to evaluate the different PFD alternatives.

**(b) Generation of the options.** To solve this issue our innovative system using a knowledge base (C-KB) enables to generate and cope with the whole response surface of alternatives.

**(c) Selection of the criteria**. Four criteria with their corresponding objectives. Every objective is quantified by one parameter or criteria index (direct indices) or more indices (indirect and subjective indices). The EDSS comprise 88 parameters (3.5.2.1 Specification Knowledge Base (S-KB)) and some of them are used as criteria indices (either direct or indirect). The total number of criteria applied depends on the user priorities:

1. *Technical* (aprox. 50 indices).
2. *Economic* (6 indices: 4 parameters + 2 methodology outputs)
3. *Env. Impacts + Sub products* (6 + 4 indices and 2 impact categories)
4. *Social* (8 indices)

**(d) Evaluation of the alternatives options. Criteria quantification.** Next, all alternative indices have to be quantified in order to evaluate them. Depending on each index the quantification is based on quantitative (mechanistic models, estimation models, ...) or qualitative parameters.

**(e) Criteria Normalization.** Every index has assigned a specific value function depending on the variables behavior of that index.

**(f) Multi-Criteria Decision Analysis:** The EDSS supports the Weighted Sum Method (WSM)

**(g) Selection of the best options**. A weighted sum is made to obtain a single value for each option. The options are ranked according to the score obtained.

Following the aforementioned scheme the data entry from the scenario definition generates an input which is used to estimate and predict the behavior of the different alternatives in such conditions. Therefore, after the propagation process, each PFD have an approximated 90 outputs from the different parameters or factors (e.g., final concentration of contaminants, total investment, and overall bulking risk). The output obtained is evaluated using both, restriction parameters and *multicriteria* analysis. Non-fulfillment of some of the established set of restriction parameters (nitrogen concentration at the effluent, maximum planned investment, ...) discards non-valid alternatives. Potential solutions left are screened using an analytic hierarchy process (AHP). The AHP is a systematic analysis technique for multicriteria decision-making and it facilitates a rigorous definition of priorities and preferences of decision makers. It will be used to determine the weights of different factors in this study. Every WWTP alternative has *n* outputs, and each output have to be considered in the quantification process of the relative importance with respect to all the other ones. This problem can be set up as a hierarchy as shown in Fig. 3.20. Both, qualitative and quantitative indices have been selected to evaluate the generated options. The quantification of criteria related to quantitative indices is carried out by means of scientific estimations and estadistical expresions, while qualitative indices are quantified based on literature review and expert knowledge.

Quantitative indices, such as operation cost and investment, are denoted by capital present value. The economic indices (or outputs) are calculated and evaluated according to the national standards for capital cost calculation of municipal projects (scenario-dependent). Also, as example, from the influent flow rate, and other required data, the dimensions of each of the preselected alternatives, through a specific equation for each technology, the approximated space requirements output for every alternative is roughly calculated. Thus, using this data and other economic equations is possible to quantify them with high accuracy. Many other indices, such as nutrients removal, $CO_2$ generated, LCA, ..., are also quantitative data and will be provided with their own equations or KB links.

Qualitative (or uncertain indices) such as need for specialized staff, visual impact, safety, ..., are usually represented by qualitative descriptions. These indices can be denoted by the subjection function of fuzzy theory. In this study, 16 qualitative indices have been taken in consideration. Indices have been classified into five grades with descriptive language including excellent, good, moderate, poor and very poor. Accordingly, the subjection grade is 0.9, 0.7, 0.5, 0.3 and 0.1, respectively. The “original” data for qualitative parameters to be compared will be obtained through the expert subjectivity.

For each output resulting from the possible alternatives generated for any specific scenario, a maximum-minimum range is being created in order to generate a comparison framework. Thus, once quantified, the effect of each output, objective or criterion, in the competing options, is normalized between 0 and 1 by means of value functions. Flores et al., (2005), considered the worst and the best options to create mathematical functions in order to evaluate the intermediate effect and to define the evaluation domain or range. In this study, also value functions are created using the quantified extreme profiles obtained. Thus, the range extremes represent the best and the worst considered situation and represents the evaluation domain, converting indices, objectives and criteria, as indicated, in normalized values between 0 and 1. In this way, once a value range is created, comparison between factors is posible.

Thereafter, using the analytic hierarchy process, the priorities and preferences of the EDSS user can be translated in an alternatives rank. The different levels of importance of the criteria are reflected through weights considered by decision makers to avoid subjectivity and randomness. In our case, the number of outputs or indices taken it into account are many in order to cope all the issues that an ideal plant should optimize to the maximum. The criteria considered in the selection of the optimal wastewater treatment alternative are the aforementioned categories: (1) Technical, (2) Economic), (3) Environmental and (4) Social.

**Figure 3.20.** illustrates a typical hierarchy system of wastewater treatment alternative selection with multiple objectives. The overall objective of the decision lies at the top of the hierarchy (Level 1), and criteria, indices and the *n*-alternatives generated previously are on the descending levels of this hierarchy (Level 2, Level 3 and Level 4, respectively).

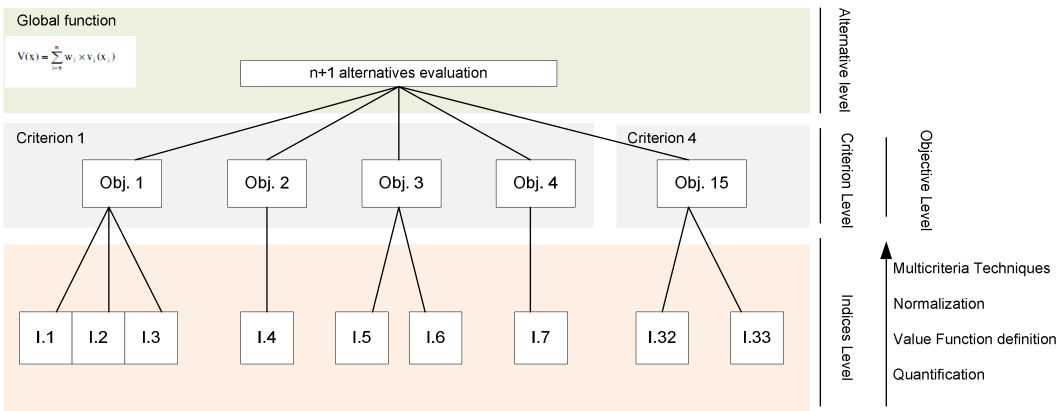



**Figure 3.20.** Our hierarchy system of WWTP Alternatives evaluation and selection.

**Fig. 3.20**. not only lists the multiple objectives, but also shows the hierarchical structure of wastewater treatment alternative selection). One or more indices can define an objective. Negative values in some indices can discard directly some alternative options. Every index is

quantified independently and has its own value function. The accomplishment grade of the overall objectives scores the alternatives.

Finally, a weighted sum is made to obtain a single value for each option. The weighted sum is calculated by adding the product of each normalized criterion multiplied by its corresponding weight. The option with the highest score is the one recommended.

$$V(x) = \sum_{i=n}^{n} w_i \times v_i(x_i)$$

It is possible to combine different techniques of multi-criteria analysis for solving this decision problem. The screened PFDs could be also analyzed by a rating algorithm (not currently implemented) or another Multi-criteria Decision Analysis (MCDA) taking in account the user priorities. Many methods, including a wide range of MCDA methods, can be used to compare quantitatively the alternatives (Keeney, 1982).Also, the Analytical Hierarchy Process (AHP), can be used to compare quantitatively the obtained PFD alternatives (Flores-Alsina et al. 2008; Ashley et al. 2008; Saaty and Vargas, 2012; Keeney, 1982). Therefore, the integrated assessment and exhaustive analysis of the alternatives results in the most suitable PFDs for any specific scenario.

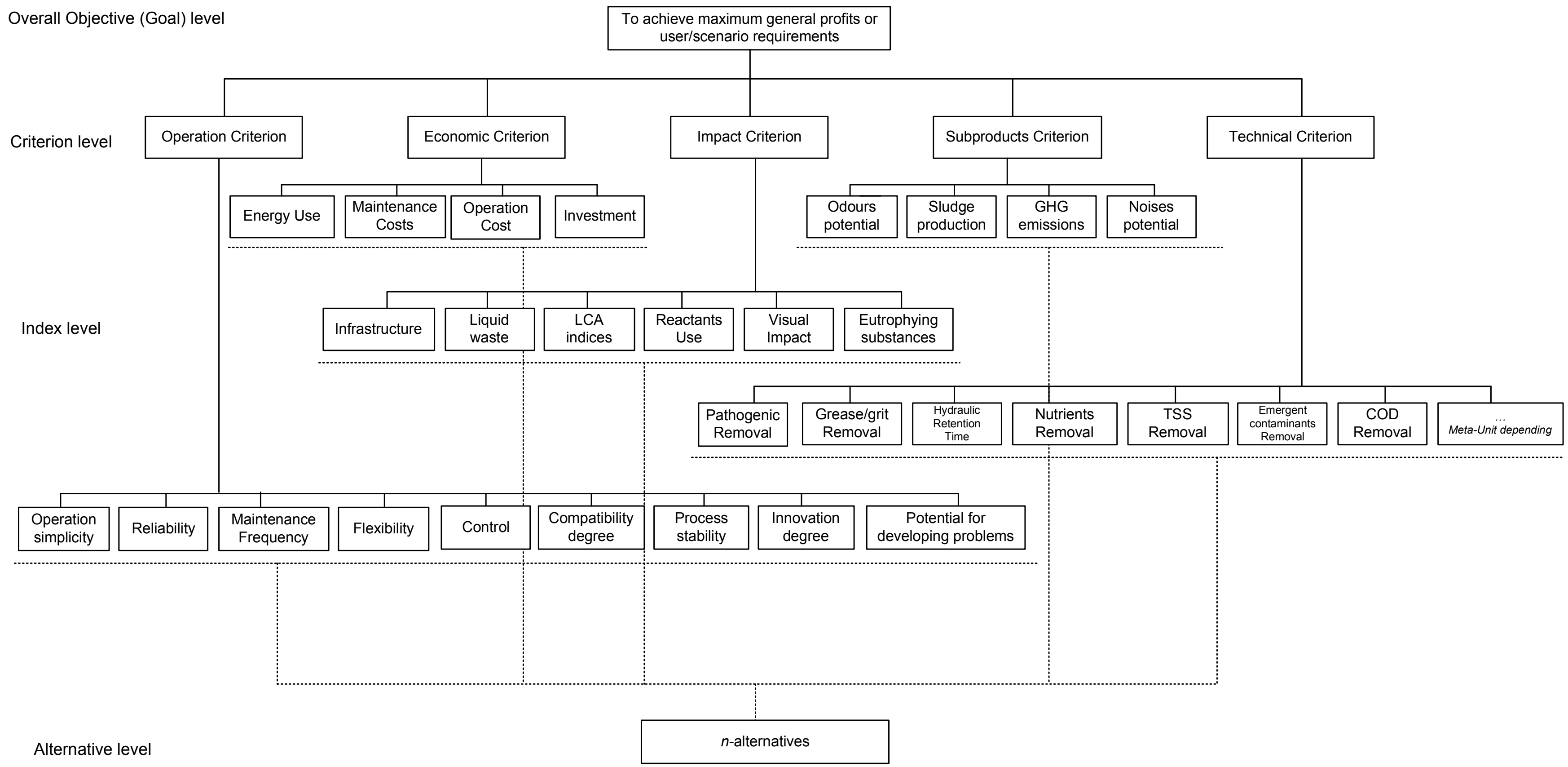



**Figure3.21.** The developed hierarchy decision model for optimizing wastewater treatment plant alternative selection. At the top of the hierarchy, the overall objective is to achieve the maximum general profits. The criteria considered in the selection of optimal wastewater treatment alternative lie at the criterion level, which mainly consist of technical, economic, impact, sub-products and performance/quality criterion. The group of indices for each criteria are also showed. The alternative level lists the wastewater treatment obtained from the p re-selection carried out during the first methodology step. Depending on the scenario, the hierarchy system can be modified according to the particular conditions.

### 3.5.7 Assessment methodologies for the integrated assessment of WWTPs.

Besides the aforementioned analytical methods that compose the NOVEDAR_EDSS (i.e. network structure, recursive evaluation, ...) two assessment methodologies for the evaluation of the created suitable PFDs to support the decision-making process were also implemented. The first methodology implementend was developed to include the environmental vector into the EDSS. For this reason, a methodology based on the Life Cycle Assessment (LCA) concept was implemented (**3.5.7.1. LCA models implementation**). The second model implemented is related to the economic vector and involves two economic feasibility methods to calculate the benefits and costs of WWTPs (**3.5.7.2. Economic models implementation**). Both methods are further evaluated and validated in **Chapter 5** and **Chapter 6,** respectively.

#### 3.5.7.1. LCA assessment methodology implementation

The general goal of the implementation of this methodology into the EDSS is the inclusion of the environmental vector in the evaluation of WWTP alternatives. In particular, our interest is focused on the identification of those environmental impacts more complex to quantify that those framed on the current existing legislation (maximum BOD effluent concetration, COD, ...), and draw a wider picture of the main contributors to more global impacts and quantify more efficiently and taking into account the sustainability paradigm.

The aim of this effort comes from the society concern that any impact, process or product produced in a specific place has more consequences that we could simply appreciate, specially, consequences in a global scale. Therefore, society requires paying more attention to these resulting impacts, currently difficult to quantify, and integrate them in products and processes assessments in order to improve and bring sustainability to our society progress model. Therefore, the implementation of a methodology able to cope with those impacts more difficult to quantify and having consequences at global scale was required. In this sense, the degree of suistainability of any WWTP that our EDSS can design can be assessed using the following implemented methodology.

The NOVEDAR_EDSS requires the right indicators to indicate how sustainable any of the wastewater treatment alternative selected is. Indicators are important instruments for supporting the decision making process, as they help to simplify or summarize important properties and to properly communicate relevant information. Thus, from all existing environmental impact indicators during the WWTP conceptual design we select the following ones:

**Table 3.5.** Elements selected for the inventory of WWTP, all data is presented for FU ($m^3$).

| Parameter | Unit |
|---|---|
| Energy use: | |
| Electricity from the grid | kWh |
| Chemicals consumption: | |
| Methanol ($CH_3OH$) | g |
| Iron chloride ($FeCl_3$) | g |
| Polyelectrolyte | g |
| Other background processes: | |
| Transport | kg·km |
| Sludge management | kg ww* |
| Other solids management | kg |
| Avoided products (1): | |
| N as fertilizer | g |
| $P_2O_5$ as fertilizer | g |
| Direct emissions: | |
| Total nitrogen (Nt) to water (2) | g |
| Total phosphorous (Pt) to water (2) | g |
| Chemical Oxygen Demand (COD) to water (2) | g |
| $PO_4^{3-}$ to water (1) | g |
| $NH_3$ to air (1) | g |
| $N_2O$ to air (1) | g |

(1) Associated to the application of sludge to agricultural land

(2) Associated to the discharge of treated water

* ww = wet weight

The purpose of this step is to evaluate the inventory with better understanding of its environmental significance (ISO 14040, 2006). To do so, the impact assessment models select environmental issues, called impact categories, and use categories indicators to condense and explain the inventory results.  All the previous elements indicators were used to calculate the environmental impact categories. Impact categories are the result to calculate the contribution to the environmental impact of the substances listed in the inventory phase in the corresponding impact assessment phase. To carry out the Life Cycle Impact Assessment (LCIA) phase, the methodology developed by Centre of Environmental Science (CML) of Leiden University was chosen (version 2.05). In our tool were used the characterization and factor values from a well-stablished midpoint method, the CML 2000, which is an update from the CML 1992 method, based on the spreadsheet version 3.2 (December 2007).

Impact categories can be divided in “mid-point” categories and “end-point” categories: Mid-point categories are categories that measure the relevant emissions and resources consumptions based on the inventory, in reference of common substances (kg CO2 eq, kg PO43- eq, kg SO2 eq…). These categories utilize well-characterized factors to measure the impact of the substances in the environment along the cause-and-effect chain on environmental processes and mechanisms. End-point categories measure the potential problems caused finally for the cause-and-effect chain in terms of tangible damage. These categories are more tangible for stakeholders, but the calculation is more uncertain than the calculation of mid-point categories. In general LCA studies the most studied categories are: abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion and any ecotoxicity categories like human toxicity, all of them are mid-point categories. Since there is not a current agreement about the impact categories to use, the categories were selected due to the fact they were considered the most relevant for this type of cases. Nevertheless, two toxicological (FET and TET) categories were implemented, although they were finally discarded as the results do not present enough valuable information

In the NOVEDAR_EDSS, due to the availability of data and previous studies indicated (Hospido, et al., 2004 and Rodriguez-Garcia et al., 2010); two main categories were chosen as best way to represent the environmental impact of WWTPs: Eutrophication (EU) and Global Warming (GW).

a) **Eutrophication Potential (EP):** This impact category has been considered the most relevant environmental issue in the majority of published LCAs on WWTPs (Corominas et al., 2011 and Lassaux et al., 2007). This impact category calculate all of the potential impacts caused by the excessively levels of macronutrients in water, the most important nutrients are nitrogen and phosphorus. This enrichment causes changes in the species composition and an increase of biomass production, in aquatic and terrestrial ecosystems. These changes can cause that the surface water is not adequate to human consumption; also the biomass increase can cause a depletion of oxygen in waters due to biomass decomposition and biomass respiration at night.

b) **Global Warming Potential (GWP).** Even when it is not among the most relevant impact categories for WWTPs (Larsen et al. 2007), GWP is usually regarded as a significant environmental problem worldwide (UN, 2010). Global warming or climate change impact counts the emissions of gases that increase the heat radiation absorption capacity of the atmosphere and causing the increase of earth's temperature that would cause adverse impacts. Normally this impact is calculated in kg of $CO_2$ equivalent, following the IPCC guidelines.

Both environmental indicators have been quantified by means of the CML[1] 2001 v2.5 method (Guinée et al., 2002), which converts all eutrophying substances to $PO_4^{3-}$ equivalent (Table 3.6) and all the greenhouse gases emissions into $CO_2$ equivalent (Table 3.7).

**Table 3.6.** Characterization factors used for EP for selected substances emitted to water.

| Substance | Eutrophication Potential (kg $PO_4^{3-}$ eq./kg substance) |
|---|---|
| Chemical Organic Demand (COD) | 0.022 |
| Nitrogen, total (Nt) | 0.42 |
| Phosphorous, total (Pt) | 3.06 |
| Phosphate | 1 |

**Table 3.7** Characterization factors used for GWP for selected substances emitted to air

| Substance | Global Warming Potential (kg $CO_2$ eq./kg substance) |
|---|---|
| Carbon dioxide, fossil | 1 |
| Carbon dioxide, biogenic | 0 |
| Methane, fossil | 23 |
| Methane, biogenic | 20 |
| Dinitrogen monoxide | 296 |

In addition to those characterization factors (Tables 3.6 and 3.7); emission factors are also required in order to include the production processes associated to the individual elements of the inventory. To do so, the Ecoinvent database v 2.2 was used (Table 3.8).

[1] CML 2001 is a LCA methodology developed by the Centre of Environmental Science (CML) of Leiden University in the Netherlands (http://cml.leiden.edu/software/data-cmlia.html)

**Table 3.8.** Background processes selected from the Ecoinvent database and corresponding emission factors for the two impact categories under study.

| Inventory parameter | Ecoinvent process | *Unit* | *EP kg $PO_4^{3-}$ eq/unit* | *GWP kg $CO_2$ eq./unit* |
|---|---|---|---|---|
| **Electricity** | Electricity, low voltage, at grid/ES | *kWh* | 0.00115 | 0.591 |
| **Methanol** | Methanol, at plant/GLO | *Kg* | 0.000408 | 0.736 |
| **IronChloride (III)** | Iron (III) chloride, 40% in $H_2O$, at plant/CH | *Kg* | 0.00291 | 0.801 |
| **Polyelectrolyte** | Acrylonitrile from Sohio process, at plant/RER | *Kg* | 0.00831 | 3.02 |
| **Transport** | Transport, Lorry 3.5-7.5t EURO5/RER | *Tn/km* | 0.000385 | 0.472 |
| **Sludgedisposal: landfill** | Disposal, municipal solid waste, 22.9% water, to sanitary landfill/CH S | *kg ww** | 0.0025 | 0.455 |
| **Sludgedisposal: landapplication** | Application, Slurry spreading, by vacuum tanker , covered/CH | *kg ww* | 0.00000217 | 0.00121 |
| **Sludgedisposal: incineration** | Disposal, raw sewage sludge, to municipal incineration/CH | *kg ww* | 0.000416 | 0.0131 |
| **Solidsdisposal** | Disposal, inert waste, 5% water, to inert material landfill/CH | *Kg* | 0.0000103 | 0.00709 |
| **N-basedfertilizer** | Ammonium sulphate, as N, at regional storehouse/RER | *Kg* | 0.0029 | 2.79 |
| **P-basedfertiliser** | Diammonium phosphate, as $P_2O_5$, at regional storehouse/RER | *kg* | 0.0552 | 1.57 |

* ww = wet weight

The implementation of this methodology within the NOVEDAR_EDSS enhances the decision-making improving the environmental understading of current WWTPS. During the operation section is provided a description to how the users can modify/update the emission and characterization factors given in its first approach (4.1.6 Life Cycle Assessment). Moreover, how this information is presented to the end-user to support the decision making is also illustrated in the following chapter (4.3. Decision support).

### 3.5.7.2. Economic assessment methodology implementation

Economic research into the design and implementation of policies for the efficient management of water resources has been emphasized by the european Water Framework Directive (WFD). Furthermore, WFD has introduced a new approach to water planning for the achievement of the environmental objectives of obtaining a good ecological status for European water bodies. The directive allocates a very important role to economic analysis.

For dealing with the requirements demanded by the WFD, especially for those related to the cost recovery for water services, economic valuation is presented as a useful tool for implementing efficient and effective policies and strategies for the management of water resources. A number of methodologies can be used as support instruments when implementing policies and selecting measurements, with cost-benefit analysis (CBA) being the most accepted and used.

The WFD requires that cost-benefit analyses (CBA) are made with the aim of identifying cases in which the adaption of measures to achieve a good ecological status for water bodies implies disproportionate costs. In this sense, all of the good benefits, including those which have nature of “non-market”, i.e., those whose values are not determined by the market, but have a high value because they likely contribute to improving welfare, and costs must be integrated into a CBA as a decision support tool.

In the water resource context, it is known that wastewater treatment has important associated environmental benefits, and in economic terms we could define this as positive externalities. However, in most cases these environmental benefits are no quantified because they have no market value. In spite of this, the monetary valuation of theses externalities is necessary to justify the economic feasibility of wastewater treatment projects. Therefore, the valuation methodologies have been developed for undesirable outputs with no market value (Färe et al. 1993, 1996, 2006;). By using the concept of distance function, a shadow price is calculated for those goods arising from human and productive activities that have no market value, but create substantial environmental impacts. Some empirical applications of this method are found in papers by Coggin and Swinton (1996), Swinton (1998), and Hernández et al. (2010).

It is important that these undesirable outputs can be considered negative environmental externalities associated with a production process. Shadow prices calculated according to this methodology represent the value of external effects that could damage the environment in the case of inadequate management. This is equivalent to the value of the positive externalities associated with avoiding the discharge pollution into the environment.

The implementation of this methodology is aimed to provide the proper assessment of PFDs to support the selection of the most adequate options in terms of minimum environmental impact and maximum economical profit. At the same time useful indicators of the economic feasibility of the operation and maintenance of the selected wastewater treatments are identified. Hence, It is particularly useful because of the integration of environmental and economic aspects. The inclusion of the economic value of the environmental benefits in the feasibility study enable to justify theselection of technologies aimed to increase the level of environmental protection.

The economic assessment through a CBA and an alternative CBA taking into account environmental externalities (the economic valuation of non-market services) is one of the novel aspects of the NOVEDAR_EDSS. The CBA is made to compare the economic feasibility associated with the implementation of different proposals. CBA main premise considers that projects should only be commissioned when benefits exceed the aggregate costs. Such analysis methodology is based on the net profit calculation for each one of the available options, which is the difference between benefits and costs (Eq. 1).

$$NP = \sum B_i - \sum C_i \qquad (1)$$

where:

*NP* is the net profit; $B_i$ is the value of the benefit item i and $C_i$ is the value of the cost item i.

In the case of investment projects whose life period is more than one year, such as the implementation of a WWTP, the costs and benefits of the project must be adjusted for when in time it occurs. For this reason, the NP must be discounted into present value terms. By means of a properly chosen discount rate, the investor becomes indifferent regarding cash amounts received at different points of time. The net present value (NPV) of an investment is calculated as a function of the NP and the discount rate as shown in Eq. 2.

$$NPV = \sum_{t=0}^{T} \frac{NP}{(1+r)^t} \qquad (2)$$

where:

*NPV* is the net present value; *NP* is the net profit at time t; *r* is the discount rate and, *t* is the time horizon of the project.

The conventional CBA, namely financial analysis, only takes into account costs and benefits with market value. However, taking into account the principles of the WFD, the benefits without market value such as environmental ones also must be considered in the assessment of the economic feasibility of investment projects.

According to Hernández-Sancho et al., (2010), wastewater treatment can be considered a production process in which a desirable output (treated water) is obtained together with pollution (organic matter, phosphorus, nitrogen, ...) using inputs (costs). Contaminants removed from wastewater are considered undesirable outputs because if they were dumped in an uncontrolled manner they would cause a negative impact on the environment. In this paper quantification of environmental benefits from wastewater treatment is based on the shadow prices values obtained by Hernández-Sancho et al., (2010) (Table 3.9). Hence, an indicator of economic feasibility of wastewater treatment technologies considering both internal and external impacts is obtained.

**Table 3.9.** Shadow prices for pollutants removed from wastewater (€/kg). Note that shadow prices are interpreted positively because they represent the environmental benefits obtained by treating wastewater. Source: Hernández-Sancho et al., 2010

| **Destination** | **Shadows prices of undesirable outputs (€/kg)** | | | |
|---|---|---|---|---|
| | N | P | SS | COD |
| *River* | 16.353 | 30.944 | 0.005 | 0.098 |
| *Sea* | 4.612 | 7.533 | 0.001 | 0.010 |
| *Wetlands* | 65.209 | 103.424 | 0.010 | 0.122 |
| *Reuse* | 26.182 | 79.268 | 0.010 | 0.140 |

The integration of this methodology within the NOVEDAR_EDSS is pioneering and enhances the decision-making process due to the integrated assessment of the economic feasibility of a set of technologies under different scenarios and wastewater characteristics considering environmental externalities.

This EDSS-economic approach is obviously designed to adapt to the characteristics introduced by the user during the scenario definition step. Thus, in the operation section is provided a description to how the user define the economic data and specific characteristics (4.1.5 Cost-Benefit Analysis), and how the final user-interface shows the results from both methodologies (4.3. Decision support).

### 3.5.8 Model integration and encoding

Integration, understood as the practical encoding of the knowledge according to the model and software selected, entails knowledge representation and codification. The data and knowledge acquired can be represented by means of decision trees, matrices and mathematical equations (algebraic or differential). These data and knowledge then have to be codified according to the software selected to form the knowledge base of the EDSS. Once the knowledge acquisition process was completed and the model selected, the acquired information was transformed into a representation which was easy for experts to understand and amend. The knowledge bases are written in Microsoft Excel. The adavantage of using Microsoft Excel as development environment is that provides capabilities that allow for analysis and manipulation of the data and the visualisation of the results. In addition, Microsft Excel is familiar, not to mention readily available, to a large majority of people. Consequently, using the program does not necessitate becoming familiar with a new software environment

The knowledge integrated within EDSS-maintenance was translated using Java language. Figure 3.22 provides an example of a rule for the selection of secondary technologies depending on some specific criteria:

```
public static ArrayList selectSecondarys()
{
ArrayList<MyNodeSecondary> res = new
ArrayList<MyNodeSecondary>();
Collection<MyNode> colNodes =
percistence.Percistence.digraph1.beta.getVertices();

for(MyNode node : colNodes)
{
if(node.isSecondary()) res.add((MyNodeSecondary)node);
}

res = evaluatingSecondary(res);
assingCriteriaValors(res);
```

**Figure 3.22.** An example of a rule for the selection of secondary technologies depending on some specific criteria.

### 3.5.9. Software design

To design a software tool an important decision is to choose the language we use to develop the software. The choice depends on several factors such as: (a) the license cost, (b) the ease of encoding and (c) its potentialities. According to these premises, the aspects considered in the selection of the Waste Water Treatment Plant Design EDSS software were:

– To prevent the software expectatives of further versions, commercial uses, ... the main applications building the EDSS not imply an excessive cost of the final support tool.

– The ability to manage large amounts of knowledge

– High level language for easy translation from knowledge to codification.

– The language had to allow the easy codification of knowledge by means of equations, mathematical expressions, IF-THEN rules, ...

With these constraints in mind, we looked for free language, and a low cost database that allow the use of such representation of knowledge by means of Network/heuristic rules. The large number of knowledge to be codified made this search not easy because free languages or low-cost databases are not usually recommended for design a EDSS.

For the design we choose these three technologies: Java (Sun Microsystems), JUNG (Java Universal Network/Graph Framework) and Excel 2007.

– Java [http://www.java.com] is a high-level, object-oriented programming language developed initially by James Gosling and colleagues at Sun Microsystems. It is similar to C++, but has been simplified to eliminate language features that cause common programming errors. Java is a general purpose programming language with a number of features that make the language well suited for use on the Web.

– JUNG [http://jung.sourceforge.net] is an open-source software library that provides a common and extendible language for the modeling, analysis, and visualization of data that can be represented as a graph or network. It is written in Java, which allows JUNG-based applications to make use of the extensive built-in capabilities of the Java API, as well as those of other existing third-party Java libraries.

– Excel [http://office.microsoft.com/en-us/excel] is a proprietary commercial spreadsheet application written and distributed by Microsoft for Microsoft Windows and Mac OS X. It features calculation, graphing tools, pivot tables, and a macro programming language called Visual Basic for Applications. It has been a very widely applied spreadsheet for these platforms, especially since version 5 in 1993, and it has almost completely replaced Lotus 1-2-3 as the industry standard for spreadsheets. Excel forms part of Microsoft Office. The current versions are 2010 for Microsoft Windows and 2011 for Mac OS X.

The Java language is chosen to implement the tool because it gives us flexibility, robustness and a large community working with it. In order to generate the graph inside the EDSS tool we use the JUNG libraries, that are based in Java but simplify the graph generation and operation. Finally we choose Excel 2007 for our database, because is very extended and the way to enter information is easier to the end user.

## 3.6. EDSS Evaluation and Validation

The EDSS must be tested to check its robustness, accuracy, usefulness and usability, both from the user's and scientist's perspective. If there are any faults at any of the development stages, the builders of the EDSS must return to a certain point of the flow diagram in **Figure 3.1** and update the required components.

When the evaluation phase is completed, the EDSS is ready to be applied. The evaluation process involves a set of tasks to identify errors or weak points in EDSSs:

– *Usability*: Difficulties for the user to understand and conveniently employ the EDSS (inappropriate interfaces, user load, documentation, ...).

– *Verification:* Lack of system specifications and poor understanding of the problem. Moreover, semantic as well as syntactic errors introduced during the implementation which would induce a not sufficiently robust (inconsistent and incomplete) system.

– *Validation:* Erroneous solutions or inability to find any solution to the problem (due to incorrect representation of the domain knowledge), causing inaccuracy.

– *Usefulness:* Unsuitable EDSS efficiency and capabilities (productivity, response time, reliability of the system response, ...).

Regarding the validation issue two main points have to been highlight: **1)** Knowledge validation and, **2)** EDSS validation.

Concerning the first point is important to remark the intention through this manuscript to point out that all information collected have been (and has to be in future upgrades) referenced at least from two or more authors. And in those cases where the information obtained had not reliable sources, or had some incoherencies in any aspect, was valitaded by any of the NOVEDAR experts involved in the project, and the same proceeding should be done in future upgrades.

Regarding the second point, the execution of a series of experiments and different trials with experts and engineers enable us to validate accuracy, correctness, consistency and usability of the acquired knowledge. When necessary, the knowledge bases were confronted against experts and the knowledge was refined, adjusted, corrected and/or extended.

Moreover, the validation of the overall results given by the EDSS is presented in the results sections as a compiling of papers. By doing so, the different aspects validate by internal project experts, trough different studies, are further analyzed by external reviewers in this set of publications to brought an extra validation in order to validate and improve the EDSS capabilities.

In that sense, **Chapter 5, 6** and **7** helps us to improve the EDSS as the software results were confronted to real cases and supervised by experts in the wastewater domain. Each of them is mainly focused in the main topics within the EDSS scope:

i) Environmental (**Chapter 5. Including the environmental vector when selecting a wastewater treatment plant**);

ii) Economic (**Chapter 6. Assessment of wastewater treatment plants design for small populations: technical and economic aspects.**);

iii) Technical (**Chapter 7. New Tool for the Integrated Assessment and Selection of Innovative Wastewater Treatment Technologies for Nutrient Removal**).

# Chapter 4

# Operating the NOVEDAR_EDSS

*In this chapter the basic concepts on how to operate and how to maximize the potentialities of the NOVEDAR_EDSS are illustrated*

# 4. OPERATING THE NOVEDAR_EDSS

In the following part is described how the NOVEDAR_EDSS is operated. Following the methodology previously mentioned (M. Poch et al., 2004) three main stages have been considered (Figure4.1): **4.1) data gathering** (with the data acquisition or scenario definition); **4.2) diagnosis** (internal software process) and; 4**.3) decision support** (results to improve the decision-making).

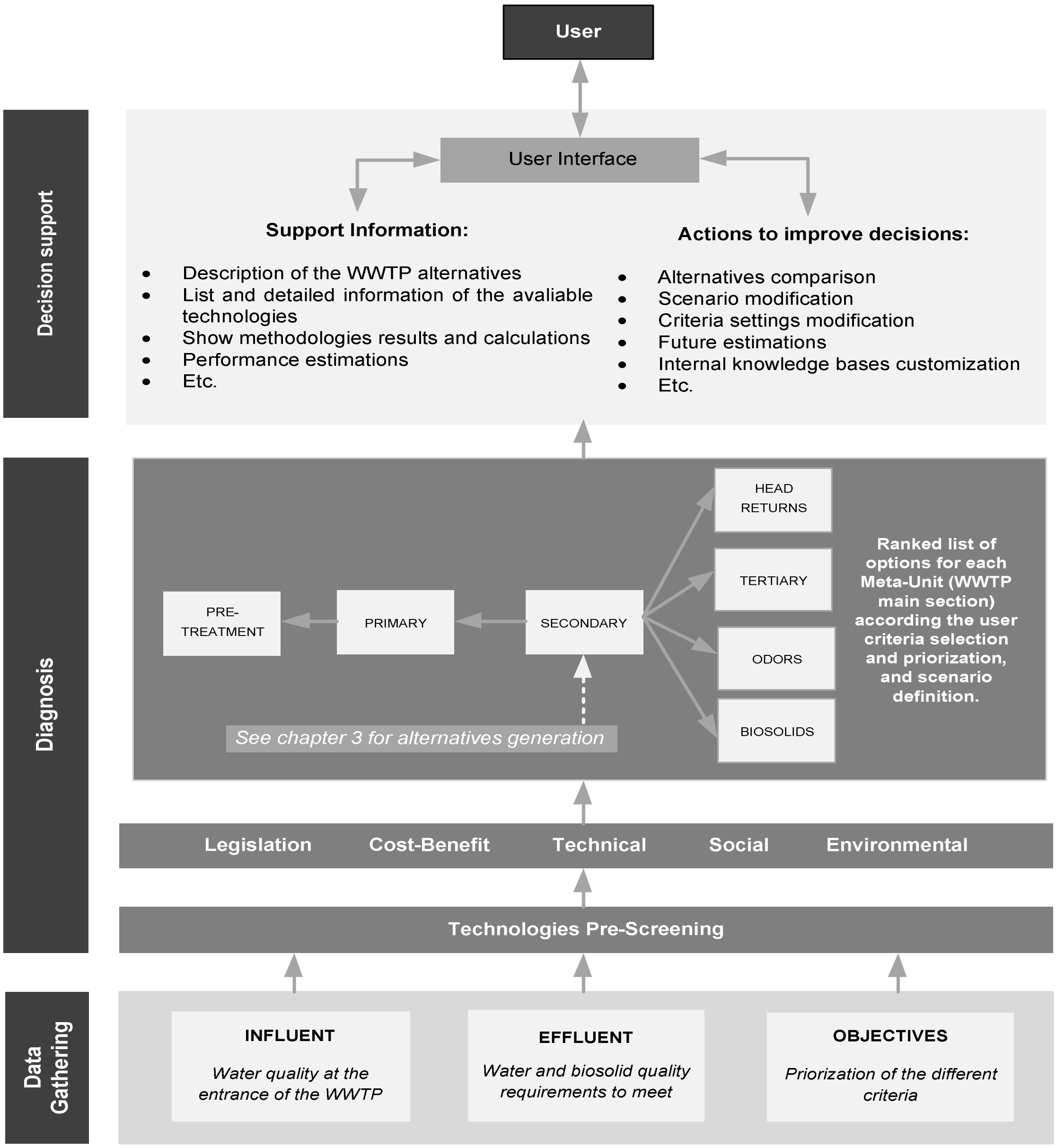



**Figure 4.1.** The operation scheme of the NOVEDAR_EDSS.

Shim et al. 2002 & Huang G.H. 2010 defined EDSS as tools capable of supporting complex decision-making through an accessible computer interface that presents results in an understandable form. Therefore, the NOVEDAR_EDSS interface has been designed to become an easy instrument to use, and intended to be very intuitive for any user while operating. In the next pages is detailed how the different tabs and stages of the expert system were designed.

The initial software menu or lobby is characterized by 5 main different sections. Only the two sections in the upper-right part are totally related to the operation methodology. The first section, a) Scenario definition, corresponds to Step 1 in the EDSS Operation methodology (4.1 Data Gathering). The second section, b) Start process, corresponds to Step 2 and 3 in the aforementioned methodology (4.2 Diagnosis and 4.3 Decision Support). Sections (c) Scenario management, (d) Libraries and (e) NOVEDAR technologies are complementary software capabilities intended to supports the decision-making experience. Therefore, they are considered as part of Step 3 (4.3.2 Decision Support Capabilities). Figure 4.2 shows the menu of the NOVEDAR_EDSS interface.


**Figure 4.2.** NOVEDAR_EDSS user-interface (Snapshot of the initial menu or lobby).

Next section, Scenario Definition (4.1 Data Gathering) introduce the input data for the community and influent characteristics, at the same time as economic, social and environmental objectives and priorities.

## 4.1 Data gathering

The first stage in the NOVEDAR_EDSS prototype is the data gathering. Data required to select and design (at conceptual level) the WWTP is introduced into the working memory through 10 different user-interface screens or tabs (one per each block of data) encompassing all the relevant categories on the wastewater treatment. For each scenario, the user introduces data concerning: (a) the community and influent characteristics, (b) the destination and final quality of the treated water and biosolid, (c) the economic details, (d) the objectives and WWTP criteria design, and (e) other environmental impacts and constraints (Table 4.1).

These interfaces convert the NOVEDAR_EDSS as a user-friendly application because they allow: (a) an easy introduction of the input data and (b) the possibility to save and retrieve this information. From Fig. 4.2 to Fig. 4.11 the different tabs within the step "Scenario Definition" to introduce the input data for the data gathering process are shown.

**Table 4.1.** Input data required for the diagnosis step

| Initial Conditions Topic | Parameters | Units / Selection Source |
|---|---|---|
| Community and influent characteristics | PE (people equivalent) | p.e |
| | Number of inhabitants (year X and X-1) | p.e |
| | Flowrate | m3/day |
| | TSS(Total Suspended Solids) | mg/L |
| | COD (Chemical Oxigen Demand) | mg/L |
| | BOD (Biological Oxigen Demand) | mg/L |
| | Total Nitrogen | mg/L |
| | Total Phosphorous | mg/L |
| | Conductivity | µs/cm |
| | Average temperatura (swwtp design) | ºC |
| Receiving media characteristics | River discharge (sensitive or not sensitive area) | Selec. |
| | Sea discharge | Selec. |
| Treated water destination | Applicable Legislation (Reuse typology) | Selec. |
| | 1. Urban uses | |
| | 2. Agricultural | |
| | 3. Industrial | |
| | 4. Environmental | |
| | Percentages for reuse purposes or discharge | % |
| Biosolid waste destination | Agricultural, composting, landfill, valorization or incineration | Selec. |
| | · Distance between the WWTP and land application | Km |
| | Type of wastewater (urban, industrial or mix) | Selec. |
| | User destination preferences (In-situ treatment, etc.) | Selec. |
| Solid waste destination (Pre-treatment) | Distance between the WWTP and land application | Km |
| Life Cycle Assessment | Eutrophication potential emission and characterization factor | Kg $PO_4^{3-}$ |
| | Global warming potential emission and characterization factor | Kg $CO_2$ |
| Economic parameters | Expected life project | years |
| | r (interest rate) | % |
| | Electricity cost | €/kwh |

| | | |
|---|---|---|
| | Reused water selling price | €/m$^3$ |
| | Biosolid selling or valorization benefit | €/ton |
| | Shadow Prices (N, P, COD, BOD and SS) | €/kg |
| **Priority-settings criteria** | Technical (stability, reliability, etc) | % and selec. |
| | Economic ( Cost-Benefit analysis, shadow prices, etc) | % and selec |
| | Environmental (landscape integration, GHG, etc) | % and selec |
| | Social (Noise and odors potential, plant safety, etc) | % and selec |
| **Pathogenic load** | Reuse legislation main pathogens (E.coli, coliforms, etc.) | Ufc, egg/L, etc. |
| **Priority pollutants** | Org. and inorg. Substances included in the priority list | µg/L |
| | Primary treatment | numeric |
| Process flow diagram | Secondary treatment | numeric |
| | Sludge treatment | numeric |

In next pages the 10 different tabs/screens that compose the “scenario definition” corresponding to relevant WWTP-related categories are described in more detail.

### 4.1.1 Influent Information

In this screen the user must specify the influent water quality to be treated (Figure 4.3). All fields need to be filled in order to continue the process. Two main alternatives methods are proposed to introduce the data related to one of the most relevant parameters in the WWTP design: The plant capacity:

1) *Fixed population*. Two fields have to be filled to indicate the required approximate capacity for the future plant. They are served inhabitants, or population expressed in population equivalent, and flowrate. Both parameters are highly relevant in order to facilitate the alternative screening of the final options. Several groups of technologies embedded in the S-KB can be organize or classified depending on their suitability to treat specific flow rates. For example, most of the SWWTPs are only suitable for population equivalents lower than 2.000. Therefore, this is one of the parameters that enables to discard easily the different groups of technologies
2) *Population growth rate*. An alternative method more widely used by plant design engineers to calculate the plant capacity is taking the population growth rate. The German official design rules, or standard protocol, always take into account this rate to prevent future expected changes due to population growth or foreseeing the industrial or economic activities growth (Hernández 2001; Bellisco, 2005; Bové 2008).

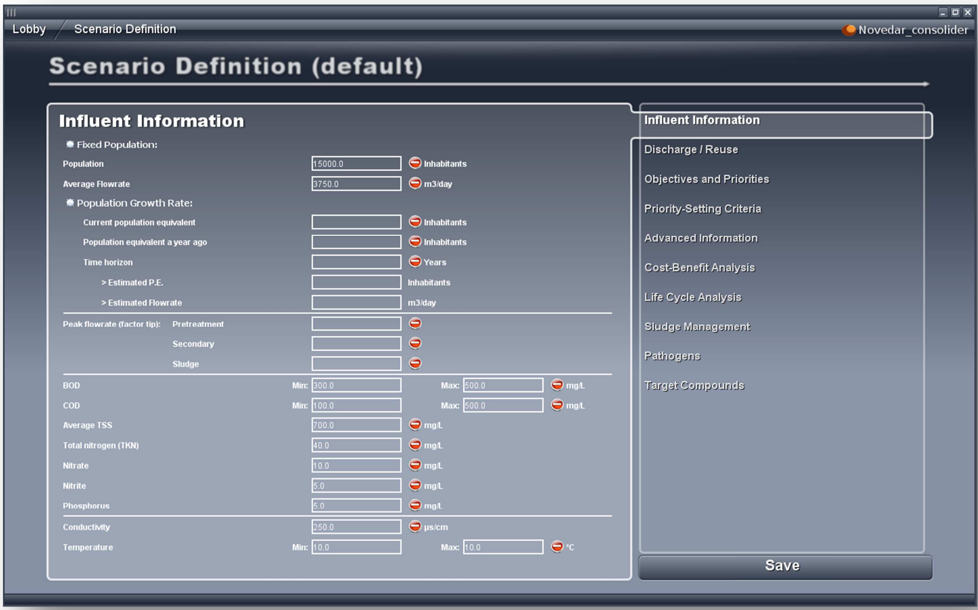



**Figure 4.3.** Snapshots of the scenario definition tab “Influent Information”.

**Peak flowrate (peak tip).** In order to provide the best approximation and taking into the economic and technical implications of a proper WWTP seizing, some safe design measures have to be taken into account in order to prevent extreme rainfall events or consider relevant seasonal variation to hinder the treatment process. Therefore, in plant design, the use of peak tips to assure a proper dimensioning and performance of the plant in such no conventional situations is essential. In this sense, although the EDSS is intended to work only in a conceptual design level, better decisions can be taken if this relevant seizing factor is taken into account.

**Influent Water quality indicators.** Current legislation and environmental standards sets the following organic and inorganic pollutants as the most used parameters to determine the water quality. The data entry of the average concentration of these pollutants at the WWTP entrance is essential to enable to the EDSS check if the different alternatives can removed and reach from those initial indicated concentrations to the final quality required (end-user depending).

***Biodegradable organics*.** Composed principally of proteins, carbohydrates, and fats, are measured in terms of BOD (biochemical oxygen demand) and COD (Chemical oxygen demand). If discharged untreated to the environment, their biological stabilization can lead to the depletion of natural oxygen resources and to the development of septic conditions.

***Nutrients.*** Total Nitrogen is comprised of the most common forms of nitrogen in wastewater in the liquid phase: organic nitrogen, ammonia, nitrate and nitrite. This field has to fill with the total concentration of all the species sum. More detailed information about the nitrate and nitrite can be proportionate to the EDSS to improve the selection suitability. Nevertheless, the lack of information about its specific species in the overall performance of global of the technologies leads that this parameter is only influencing a limited number of specific cases. . Both nitrogen and phosphorous when discharged in the environment can lead to the growth of undesirable aquatic life.

There is presently much interest in controlling the amount of phosphorous compounds that enter in surface waters either from domestic or industrial wastewaters. Therefore, the corresponding Phosphorous field (mg/L) must be also filled with the sum of the usual forms of phosphorous that are found in aqueous solutions (orthophosphate, polyphosphate, and organic phosphate).

**Electrical Conductivity**. The electrical conductivity of water is one of the important parameters used to determine the suitability of water for irrigation. Although only a few specific technologies are sensitive to treat high-strength industrial wastewater (due its high salinity), it is important the identification of such cases to allow the EDSS propose the suited options. Nevertheless, extreme salinity in the influent has to be prevented and even some legislation sets maximum values in its entrance (Poch, 2008). Therefore, this maximum is set in all technologies, and in case those concentrations were meet the EDSS warns to the end-user that specific attention should be paid to solve this problem by a more detailed study.

**Temperature.** The temperature field in this tab, at present, is exclusively referred to those options related to low-loaded technologies that their main biological processes are more dependent to outside conditions than conventional extensive treatments. Therefore, only technologies as constructed wetlands, green filters, trickling filters, … are going to be sensitive to this parameter value. Intensive technologies as activated sludge are also dependent of this value. However, the temperature effects are less relevants and since there are not good estimation to predict its inlfuence in the overall extensive process is not going to be implemented. The values required in this field are related to a yearly average. Although temperature dynamics can be relevant through seasonal variations, the ranks are according of the minimum and maximum within one year. However, the temperature rank provides information about the suitability of the options, although do not discard SWWTP (except extreme climatical situations) any option.

### 4.1.2 Effluent Discharge/Reuse

In these tabs the user must indicate the final destination of the treated wastewater and generated biosolids (Figure 4.4). Based on the option indicated by the user, the system supports the decision meeting the appropriate legislation. Thus, once the user selects the final destination of the water, the EDSS screens those treatment options that are able to achieve the corresponding quality requirements.

Two main options or final destinations are proposed to the end-used for the treated wastewater: Reuse or Discharge. In order to promote the reuse of the treated water, according the new sustainability paradigm, the first section of this tab is exclusively framed to the Reuse legislation embedded in the Spanish Royal Decree (1620/2007). Five different sub-tabs are displayed showing the different reuse categories that can be found in this legislation. For every category, different options with more detailed information can be chosen. If the reuse option is the desired, the user has to select the different options within any of the categories, after that the EDSS match the selection with its corresponding quality requirements for such reuse. Therefore, after the selection, the EDSS starts to screen all those technological combinations that are able to meet the corresponding requirements considering the initial influent characteristics. In those cases where most than one option have been selected, either in the same category or in a different one, the most quality restrictive option is applied by the system set as the limiting one.

The user can choose the quantity of treated water that can be used for reuse purposes or discharge. In many cases the amount of treated water is bigger than the current reuse needs, so there is no interest to treat all the water to the same quality level (savings in chemicals and energy). For this purpose, an slide bar enabling to modify the exact flowrate ($m^3$) which have to be treated for each main typology of reuse/discharge option was implemented. The flowrate changes (either discharge or reuse purposes) at same time user moves the slide towards the required volume.

Discharge options are related to the corresponding legislation framed by the Water Framework Directive (Directive 2000/60/EC) and the Spanish regulations. Three main discharge options with its respective specific quality requirements are possible: a) Discharge in sensitive area; b) Discharge in non-sensitive and c) sea discharge.

Moreover, other discharge option framed in the Spanish legislation is discharge in wetland areas. Nevertheless, as the quality required for this destination is similar, or even higher, than some of the reuse options, the slide has been set in an upper position than the discharge options. In this sense, Wetland destination slide is implemented more likely as an alternative option closer to reuse rather than the rest of discharge.

For both reuse-related options the slides can be displaced freely by the user. By displacing the slide the corresponding percentage and the flowrate ($m^3$/day) are changed simultaneously. The flowrate value used is taken from the previous tab (Influent information).The sum of both options (Reuse and Wetlands) cannot be higher than the 100% of the influent flowrate. When the sum is lower, corresponding rest is going to be calculated for the selected discharge option.

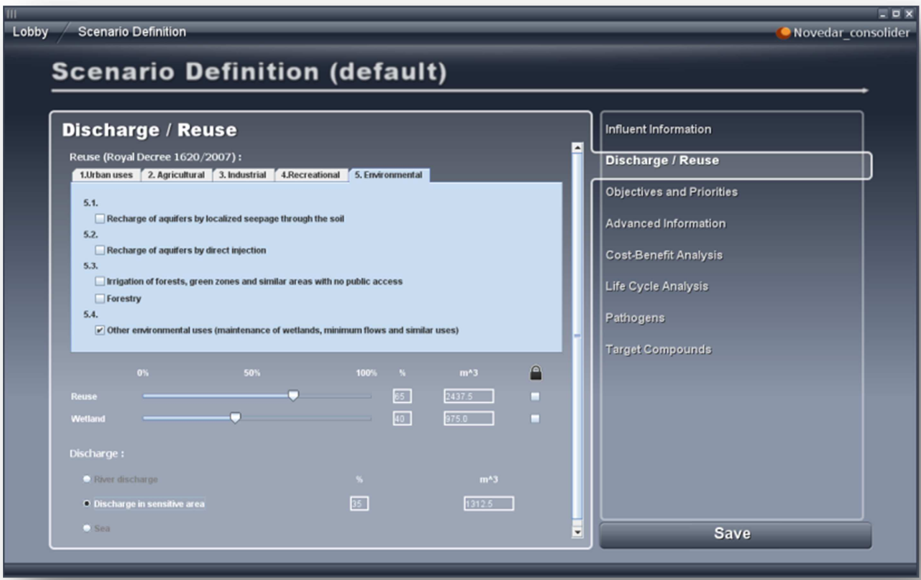



**Figure 4.4.** Snapshots of the scenario definition tabs: Discharge/Reuse.

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### 4.1.3 Sludge Management

In the tab corresponding to sludge management the biosolid destination (Figure 4.5) and final characteristics options are based on the current Spanish legislation framed in the *Plan Nacional de Lodos de Depuradoras de Aguas. Residuales 2001-2006 (PNLD)*. Main guidelines of this framework are graphically illustrated in this tab in order to promote the knowledge of the current trends and good practices in this important section of WWTP, even in economic terms (up to 40% of costs). The first section has two main selection options:

**Type of wastewater.** The user should select the main source origin of the sludge. Industrial and urban bio solids can differ from its composition properties and the proper management for each type should be different and specific. Therefore, by selecting this corresponding option the screening process can be improved. At the moment, the industrial module is not implemented yet, and this option is not operative at this current thesis state.

**User preference:** This option is essential in order to trigger the design of sludge trains by EDSS. When the user choose the option In-situ biosolid treatment the EDSS is ready to look for those sludge train (or suitable combination or biosolids-related technologies) that can match with the specific scenario. Nevertheless, the Conveyance and Ex-situ treatment option stops the EDSS to search for the suitable sludge line. Therefore, in those cases where the user already knows the future sludge train structure or do not need the design of this section, by clicking this option the EDSS do not provide further information about this issue. Moreover, this option can be useful for specific studies (LCA, CBA, etc.,) where the interaction of the solids line in the overall plant wants to be excluded (partial retrofit studies). Due the complexity to design sludge line for a WWTP this option allows the system to improve the speed of the EDSS conventional performance.

After that, if the user has selected the *In-situ option*, three more options to select are displayed, related to the main typologies of biosolids treatment can be chosen. Depending of the selected option some groups of technologies related to the treatment plant are discarded or selected in order to screen more effectively for suitable option. For example, when the composting option is selected those clusters of technologies combinations, involving incineration-related technologies or energy valorization technologies, are discarded for further assessment analysis.

The user can, also, indicate the approximate distance from the theoretical plant location to the closer point where the biosolid is expected to be applied or composted/valorized or incinerated, or disposed. No influence in the technology combination selection is derived by the distance registered, however, is recommended to fill in this specific data in order to have a better assessment in the environmental vector (LCA) if such criterion is going to be somewhat prioritized.

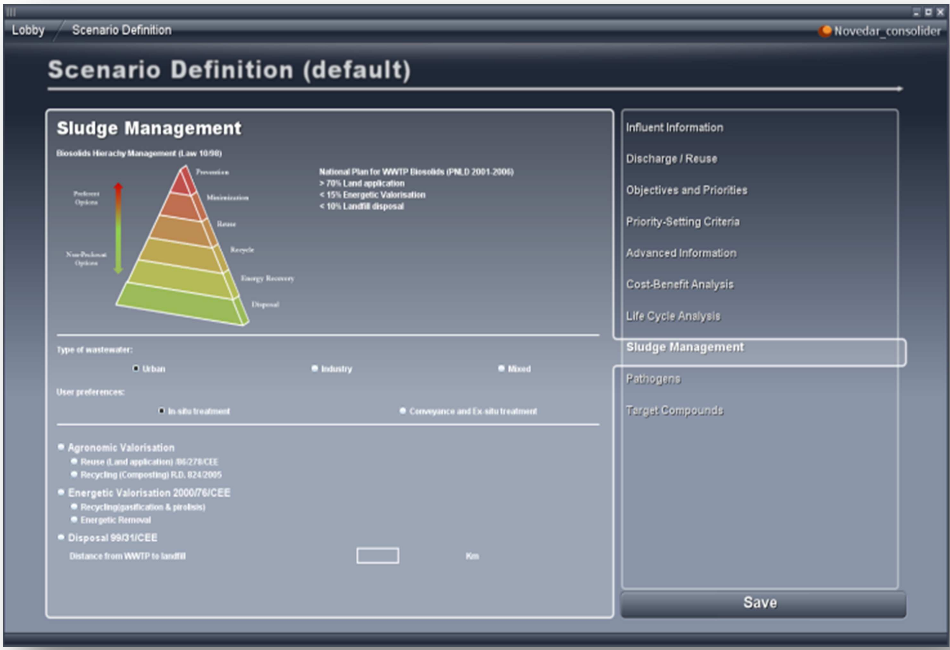


**Figure 4.5.** Snapshots of the scenario definition tabs: Sludge Management.

### 4.1.4 Objectives and Priorities

In this screen snapshoot the user can decide at what degree prioritizes different objectives that can be pursued during the design of a WWTP (figure 4.6). Four main slides corresponding to the four main criteria: Economic (COSTS), Environmental, Technical (OP/TECH DATA) and Social are set in order to facilitate the multicriteria exploration of the alternatives response surface. The displacement of any of the slide bars varies the preference of the selected criteria. The user can also indicate/select the specific parameter (or targets) from the list composing each criterion or objective, and the EDSS takes them into account during the multicriteria analysis Therefore, the different parameters composing the final objective value can be selected or deselected, at the same time that can also be prioritized in consideration of the other parameters in this specific objective. For example, in the economic section, the user might find interesting to take into account during the WWTPs alternative assessment both cost-benefit methodologies implemented in the EDSS but not in the same degree of weight. Therefore, the users have to select both of them, and adjust thereafter the specific weight in each of them. Thus, the users can select which set of variables wants to prioritize (Social / Environmental, Cost, Technical, or Operation).

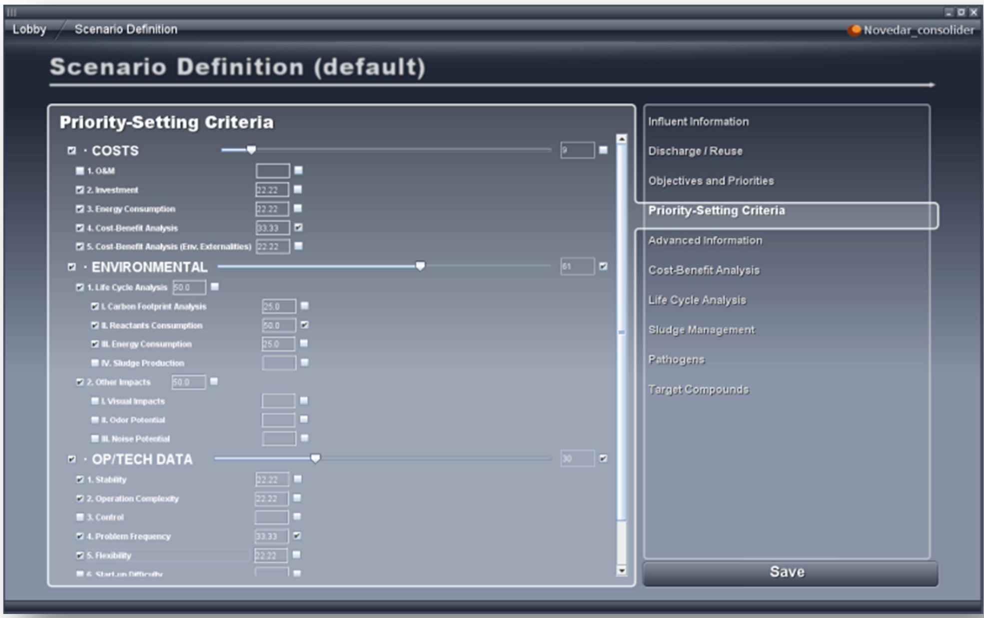


**Figure 4.6.** Snapshots of the scenario definition tab related to criteria and objectives prioritization.

### 4.1.5 Cost-Benefit Analysis

The display is characterized by two main parts (Figure 4.8). One of them offers the possibility to modify some predefined data related to the conventional Cost-Benefit Analysis (IRR, NPV, etc.). The second part supports the methodology related to the environmental benefits quantification from the group of Francesc Hernández (University of Valencia) (**3.5.7.2. Economic models implementation**).

The first part (Figure 4.7) is being designed to proportionate, to the end-user, the chance to carry out a simplified Cost-Benefit analysis of different alternatives proposals in order to compare their economic feasibility. Such analysis methodology is based on the net profit calculation for each one of the available options, which is the difference between benefits and costs. Although electricity use, bio solid production, and other-related data are calculated by the EDSS, the conversion of these parameters to final costs and benefits requires from the end-user some information due the geospatial and time variability of this type of data (€/m3, €/kwh, €/kg biosolid, etc.). Energy price can vary from different areas, subsides and trough time. The same for the reuse water price and biosolid. In the case where sludge sub-products can be valorized as positive economic value and a source within the plant benefits its price in the market will vary from each case. Therefore, the end-user should indicate in this tab the scenario specific data related to this issue in the case of any or both sources can be valorized.

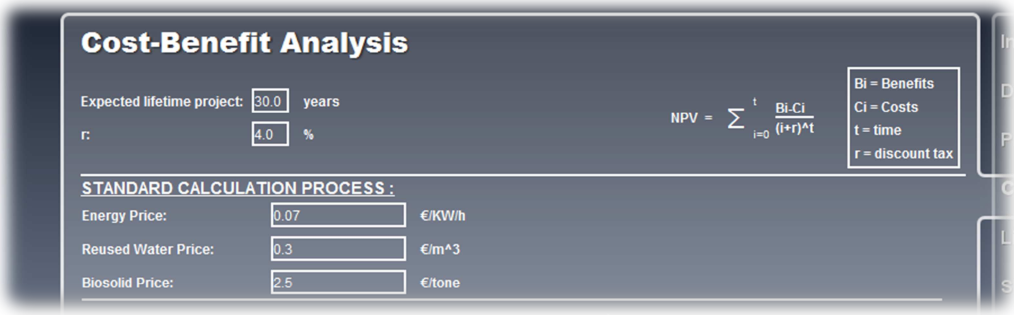


**Figure 4.7.** Screen capture zoom of the EDSS showing the parameters related to the conventional Cost-Benefit Analysis within the Scenario Definition slide. The required factors (i.e. Plant expected lifetime, Return Tax, etc.) are displayed in top of the slide.

The second part of this tab (Figure 4.9) is related to the environmental benefits quantification using the so-called shadow prices and transforming the avoided environmental impact into an economical benefit. This section pretends to show to the decision maker (DM) or final user the shadow prices values that are used when this methodology is applied. These values were calculated following the aforementioned methodology of the UV (NOVEDAR_Consolider partner). More information about this methodology can be found at Molinos-Senante, 2011 and 2012, and section 3.5.7.2. Economic models implementation. In the cases the EDSS user feels confident to provide different values, or taking into account that some of the shadows prices could vary in the future (climate change, etc.), or even, with analytical or scientific purposes, the user can modify and customize this values just clicking twice on the select value. Reset to initial values button was being implemented in the moment of this thesis was submitted.

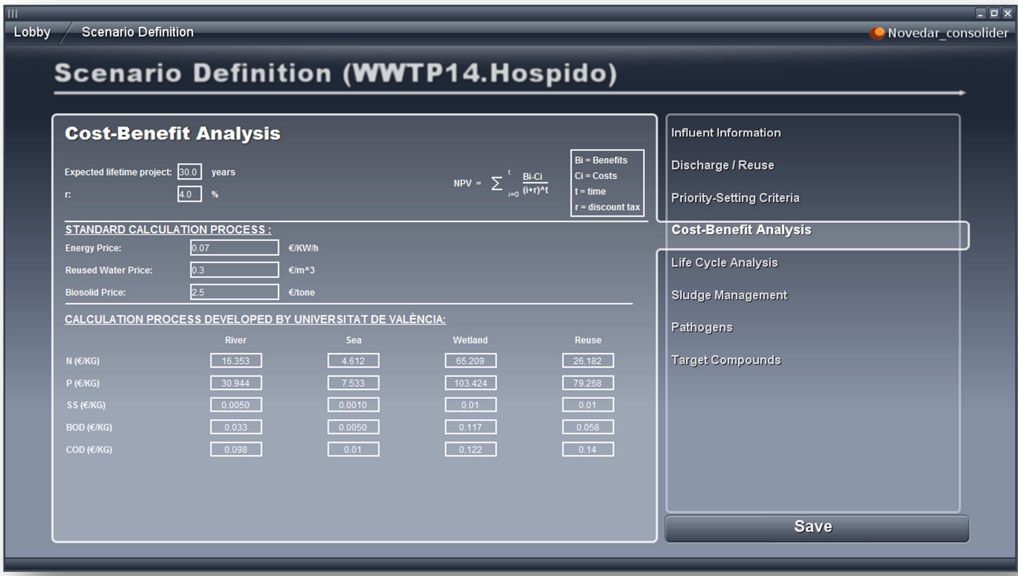


**Figure 4.8.** Screen capture of the economic section in the EDSS data gathering

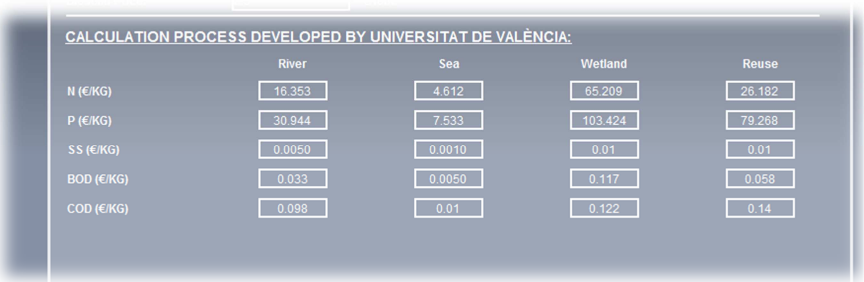


**Figure 4.9.** Screen capture of the EDSS data gathering interface and zoom of the default factors to apply when using the innovative approach by F. Hernández 2000.

### 4.1.6 Life Cycle Assessment

The purpose of this tab (Figure 4.10) could be properly defined as purely informative. All the characterization and emission factors from the implemented methodology of LCA to convert the inventory data of each PFD to a quantifiable environmental impact (Eutrophication and Global warming) are shown. The quantification or inventory transformation to these categories enables to carry out a Life Cycle Analysis for each WWTPs alternatives, and this can be further used in the multi-criteria step of ranking options. In this sense, the values that are currently implemented where extracted from the SimaPro 7.3 software (http://www.pre.nl/simapro), one of the most commonly used software tools for LCA studies.

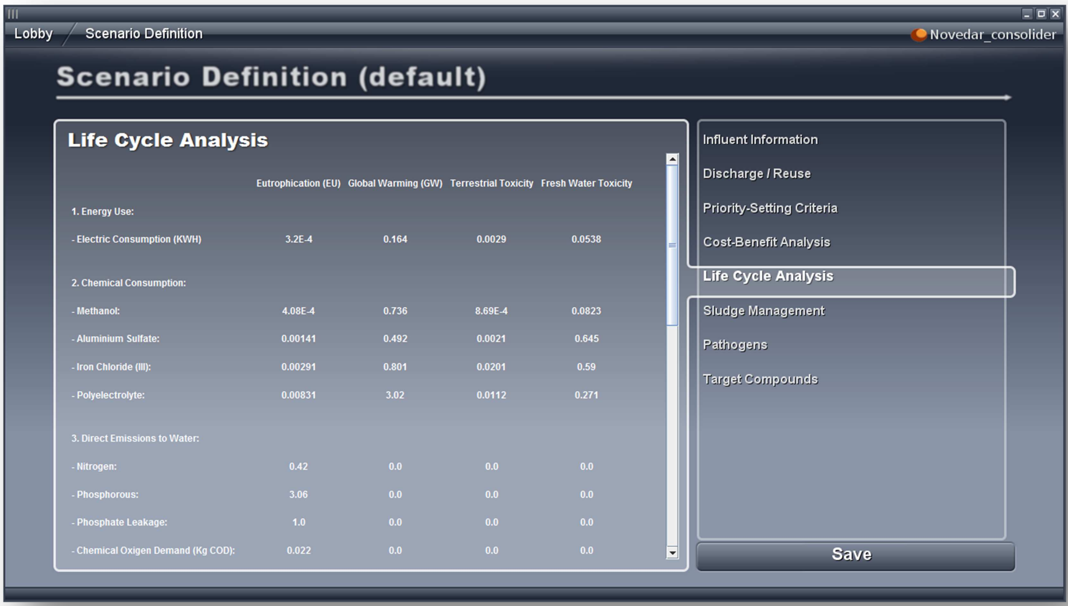


**Figure 4.10.** Screen capture of the EDSS showing the Scenario Definition slide about the emission and characterization factors for the inventoried parameters and processes (Ecoinvent factors - SIMAPRO, updated in 2002).

### 4.1.7 Pathogenic Load

Communicable diseases can be transmitted by pathogenic organisms that may be present in wastewater, and specific legislation is set to establish the concentration limits at WWTPs effluents before their discharge or reuse. Therefore, this tab offer to the end-user the chance to introduce into the EDSS the concentration of pathogens that could be found in WWTP influent (if known), and the EDSS will estimate their removal and final theoretical effluent concentration.

The selection of the pathogens was established according the main reuse water indicators used by the Spanish legislation for water reuse (Royal Decree 1620/2007). This legislation sets a minimum concentration of these pathogens in all typologies of reuse water establishing the legal framework for the reuse of treated water. Therefore, when the userselects this option it is highly recommended to fill or update properly these fields. In those cases where the user do no known the exact concentration of pathogens the EDSS provides default values taken from the literature (from scientific references).

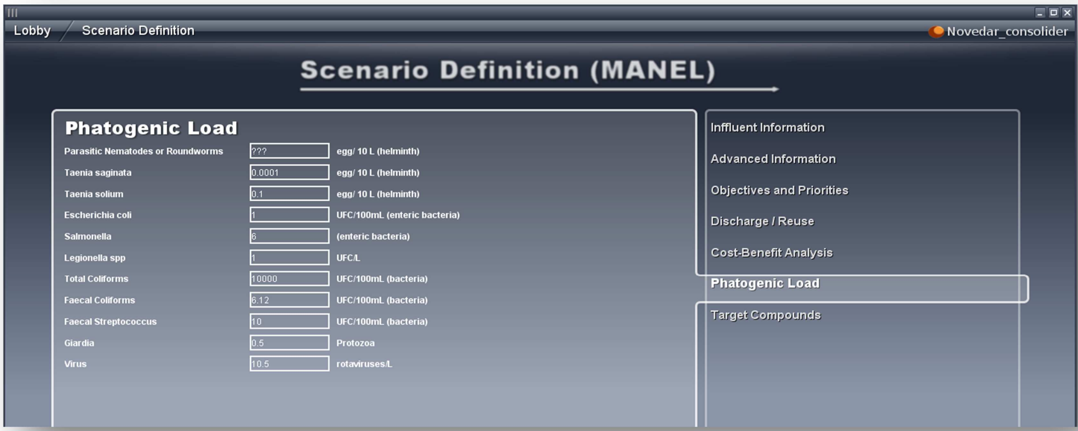


**Figure 4.11.** Screen capture of the tab corresponding to the pathogenic load during data gathering process.

### 4.1.8 Target Compounds

In last years, the society concern about emergent contaminants, most-known as pharmaceutics and personal care products (PPCPs), increased. Although there is a legislation on Environmental Quality Standards for surface water, about priority substances, where some of PPCP can be found: Directive 2008/105/EC there is no any mandatory clause (due its low concentration levels and not yet proven damaging health effects). Nevertheless, as its interest have been increasing since the last years on the basis of their known or suspected carcinogenicity, mutagenicity, teratogenicity, or high acute toxicity, these tabs offer to the end-user the chance to introduce into the EDSS (4.12) the concentration of some of the most common substances that have been reported in WWTPs.

18 emerging contaminants are part of some of the research being developed at the University of Santiago de Compostela (USC) and University of Barcelona (UB). Different projects within the Novedar_Consolider consider the selected target compounds, and from their works approximate estimations about its concentration at the effluent of the different options were obtained. Thus, the removal efficiencies of different technologies were obtained both from the some of the NOVEDAR_Consolider partners (USC) and scientific bibliography.

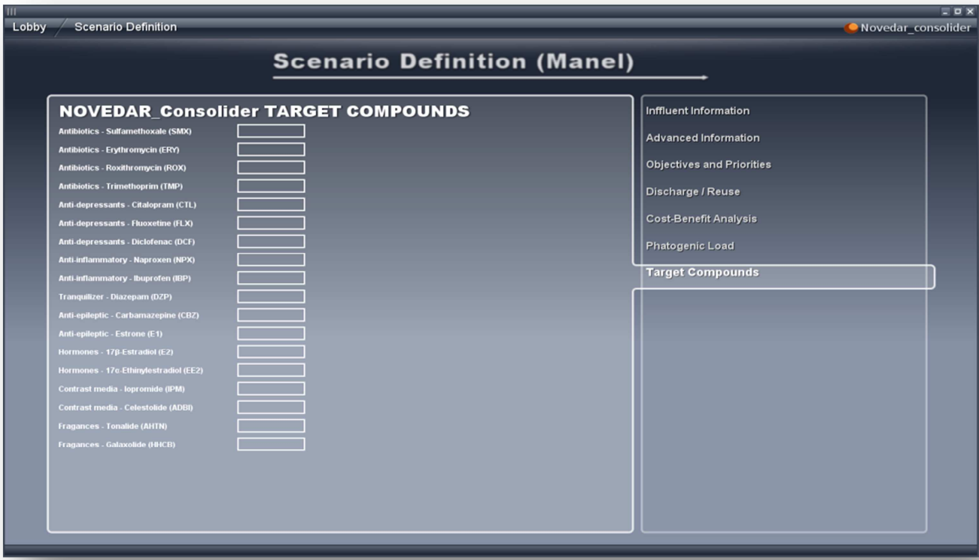


**Figure 4.12.** Screen capture of the tab related to 18 selected target compound (or priority pollutants).

## 4.2. Diagnosis

The second step of the NOVEDAR_EDSS, diagnosis, includes the reasoning procedure that is used to infer the state of the process so that a reasonable proposal for the conceptual design of WWTP alternatives can be given. This reasoning process has already been presented in Figure 4.1.

Relation summary between the data gathering process and the diagnosis step:

- From the influent characteristics, and some WWTP design details, EDSS identifies suitable technologies, and discards any option that could not meet such specifications.
- From the effluent destination and sludge management, EDSS defines the required effluent and bio solid quality at the end of the water and sludge line respectively.
- From the objectives and priorities the multi-criteria can be customized, consequently the resulting options can be scored according to those user preferences.
- From the cost-benefit analysis tab the economic characteristic of the project can be introduced to enable the EDSS calculate the economic criteria.
- From the life cycle analysis update tab the emission and characterization factor can be upgrade easily to meet future modifications in used databases.
- From the pathogenic load and target compounds tabs the EDSS incorporates an initial or start values to use in its estimations to match more efficiently the final recommend WWTP option
- Finally, from the whole set of the input data, the EDSS calculates, identifies, scores, and shows to the end-user the diagnosis results in an understandable form.

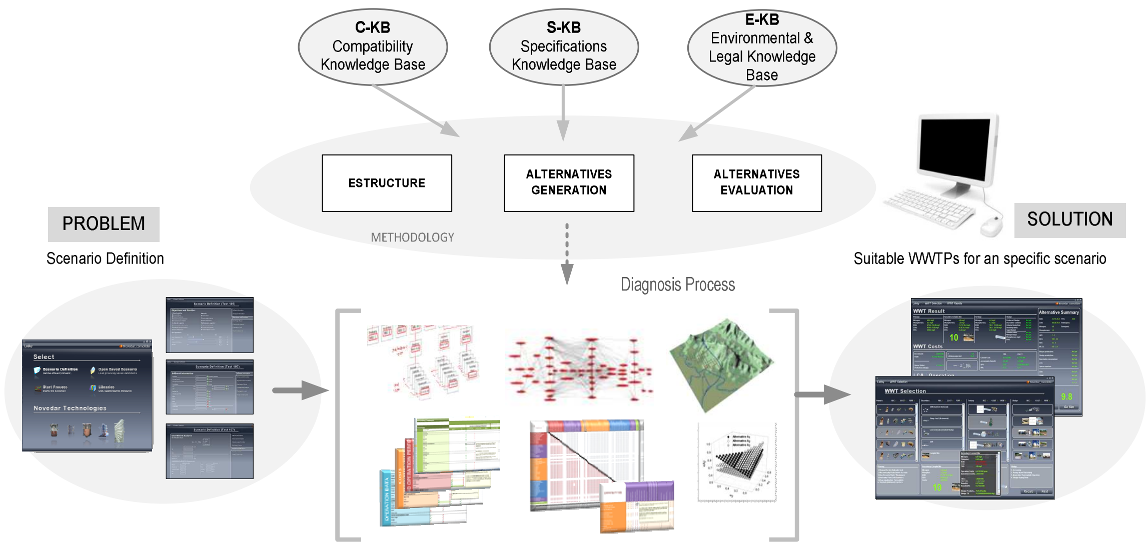


**Figure 4.13.** General and simplified diagnosis methodology scheme.

This procedure is accomplished with the help of the DPM (Data Processing Module). This second step takes place after the end-user press the corresponding button in the section (**Start Process)**, once the scenario definition was fulfilled. The required calculations take place in order to check the best option of WWTP alternative according such scenario. Two main steps are required following this methodology (Figure 4.13): 1) Generation of the whole response surface of PFD alternatives; 2) selection of the PFD that meet the specified requirements by an integrated assessment of each option.

### 4.2.1 Diagnosis Steps

*Step 1: Generation of the whole response surface of WWTP alternatives*

As shown in **Chapter 3.5** the model selected enables that the information collected in the matrices about technologies compatibilities (C-KBs) and technologies characteristics and specifications (S-KBs) can be converted to an interconnected group of technologies in the form of a network (or cluster diagram) integrating the whole response surface of suitable alternatives in a single and functional directed (or oriented) Network Structure.

*Step 2: Selection of WWTP configurations adapted to specific scenarios.*

Following the aforementioned procedure once all suitable WWTP alternatives solutions have been created is time to select only the ones that accomplish the degree of satisfaction. To do that, a network structure, by means of a data processing module, achieves the capacity to transfer, transform and manage different types of data (**3.5.3. A Structural Network approach for the generation of PFDs**). The flow paths between units (obtained from C-KBs) can be used as functional connections that are able to send and save information from one node to another. The network becomes, then, a functional system able to carry out a recursive evaluation of the treatment trains (**Section 3.5.5 and Section 3.5.6**).

The data processing module is also responsible to detect the alternatives embedded on the network and extract them as single flow diagrams. Then, the assessment of the multiple technological combinations can be carried out. For the evaluation of each possible flow diagram is necessary to take into accounting the data introduced by the user during the Data Gathering **(Section 4.1**). Therefore, a recursive evaluation is possible by the interaction of the introduced data during the Data Gathering with the information available in the nodes. During the evaluation the data is transferred through the combination of the different nodes composing every single flow diagram. Consequently, the data is being modified/used by equations, expressions and other data linked to each node composing the flow diagram (as nodes are linked to the S-KB). Later on, as the data processing module saves the resulting output from every node in any treatment train is possible to evaluate independently every WWTP alternative. In that way, the evaluation enables the comparison of the theoretical performance of the different alternatives in a specific scenario and, finally, selects the alternatives that meet all the required objectives.

After the evaluation of the whole set of embedded treatment trains the desired output is attained. All treatment trains have been scored. Therefore, a set of outputs in an understandable form (either using suitable flow diagrams, technology scoured lists, information tabs, etc.) is provided through the specific designed interface in order to support the decision-making process.

## 4.3 Decision Support

Two main sections within the Decision Support could be distinguished according their involvement degree in the EDSS methodology. The one exclusively related to the main methodology functioning (**4.3.1 Start Process**) and the one including some extra capabilities which were set to enhance the decision-making process (**4.3.2 Decision Support Complementary tools**).

The first group, Start process, corresponds to the **4.2 Diagnosis** and the **4.3 Decision Support** stages. Second group (*Scenario management, Libraries and NOVEDAR technologies*) is also considered as part of the **4.3 Decision Support.**

### 4.3.1 Decision Support: Start Process

After the data gathering, the diagnosis step takes place. In this stage, the system selects those technologies that offer the most suitable solution to the specified conditions. Nevertheless, before the system provides a definitive WWTP PFD some involvement from the end-user is required. The user involvement is based in a general selection procedure following a hierarchal process.


**Figure 4.14.** Snapshots of the lobby (focused at the Start process section).

Once the first step is completed: Scenario Definition; the EDSS has all the required information to start the diagnosis process. Selecting the Start Process button the first screen to start the PFD design is shown. Due the importance of the secondary process in any WWTP, the rest of the PFD cannot be generated without this important plant section. To solve this problem, and in order to proportionate to the user more decision capacity in the final PFD, the general procedure to select WWTP alternative have been split in different parts corresponding with the main sections in a WWTP, and has been designed following a certain hierarchy. Therefore, in the beginning of the selection process, the EDSS shows a list with the better scoured secondary technologies. Therefore, the EDSS provides a list with the most appropriate secondary technologies from highest to lowest degree of satisfaction.

After the secondary treatments list is generated, ranked according the scenario definition, the user can select any of the provided options. By doing so, the EDSS is ready to calculate and check which combination of primary (including pre-treatment), tertiary and biosolids treatment (including thickening, stabilization and dewatering/conditioning treatments) are recommended for that particular secondary treatment.

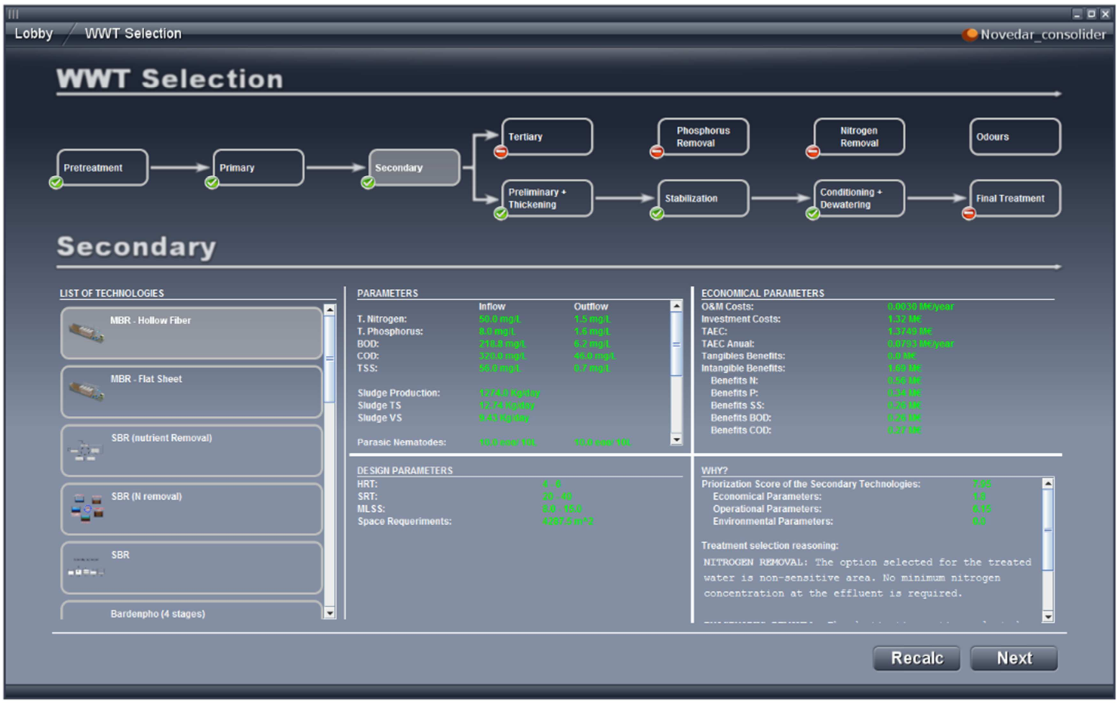


**Figure 4.15.** Screen capture of the Start Process section during the secondary selection.

The most favored options for any of the different sections are always placed upside down (Figure 4.15). From the different lists, according the different plant sections, the user can choose between the best scoured options in the main parts of a WWTP. Basic information regarding the efficiency and other specification of any treatment are shown in the bottom of each tab in order to assist in the selection process. Even, if the user, or decision maker, requires more information or also needs some more insight about any technology, the possibility to access to the library (**4.3.2.2 Libraries**) and check out the datasheet could be helpful option.

### 4.3.2 Decision Support: PFD Results

Once the different WWTP parts have been selected and a complete WWTP alternative or PFD has been created, the EDSS program displays the results (Figure 4.16) that would support the decision-making. The EDSS displays the results in specially designed interface screen where the most important information for the decision-maker is shown. The WWT Results screen consists in four main parts: Technical part, economic, environmental/social and operational. Moreover, the right-hand can be found a section where the most relevant information of the above sections is summarized and where extra information that may be essential is included


**Figure 4.16.** Snapshots of the results interface showing the PFD outputs for a specific scenario once the WWTP line have been selected.

Next a detailed explanation of the results screen (WWTP Results) is presented:

### 1) Technical section

In the upper left part the expected results of the quality of the water after being treated by the previously selected technologies are shown. It also enables to see the quality improvement through the different parts of the WWTP (pre-treatment, primary, secondary, tertiary, if required, and treatment of biosolids). The basic parameters of quality are described by the following parameters: COD, BOD, TSS, Nitrogen and Phosphorous concentration, pathogenic concentration. Biosolids section has their own place in this screen where their functioning process is descried.

### 2) WWT Costs (Part economic)

According the economic methodologies previously described, this section displays the corresponding cost-benefit study of the selected plant. In the left side of this section all the most important values to carry out such analysis are shown: Operational costs, capital costs, maintenance, amount of water that can be reused (benefits) and more specific parameters such as the IRR, r (taxa of return) and the NPV applicable.

In the right side two columns are found (Figure 4.17). The first one corresponds to the values obtained by performing a conventional cost-benefit analysis, and the last column, on the other hand, corresponds to the same CBA but taking into account the environmental benefits of the methodology of the University of València (UV).


**Figure 4.17.** Screen capture of the EDSS in the final stage: Select WWTP summary. After the PFD selection a section in the summary about both economical approaches is shown. The main parameters influencing the economical values (Benefits: from biogas, from sludge valorization and treated water selling; Costs: O&M, investment and course costs) are displayed at the right side of the final results of both approaches.

### 3) LCA / Operation (Part Environmental / Operational Part)

The frame placed at the bottom left side (Figure 4.18) corresponds to the estimate Life Cycle Assessment (LCA) of the plant. This analysis is performed using the aforementioned methodology implemented by the collaborative process with the USC. Both categories: Eutrophication and Global Warming values are displayed altogether with the corresponding inventory for the selected alternative. The estimated inventory is thoroughly detailed in this section. Using the section slide all the impact indicators (energy use, chemical consumption, etc.) that comprise the two environmental impact categories can be reviewed.

Additionally, the right part of this section is intended to provide information on social issues such as: noise potential, odour potential and visual impact. And also, a module to offer suited alternatives for eliminating odours is expected to be finish by the end-of the year.

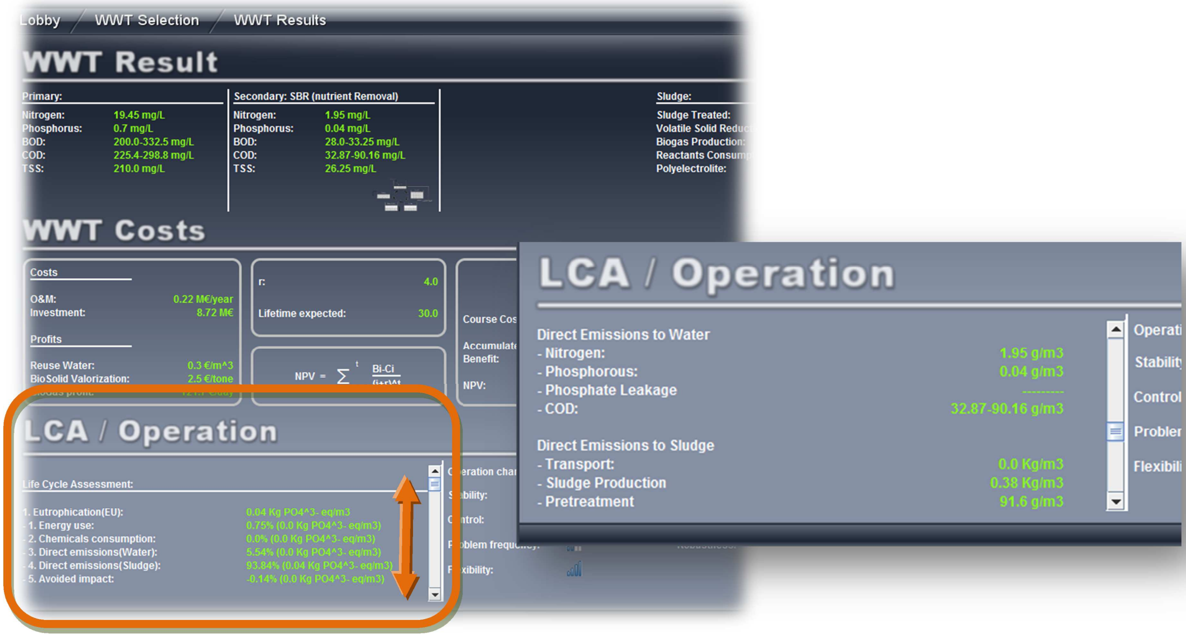


**Figure 4.18.** Screen capture of the EDSS. After the PFD selection a section in the summary about the LCA and its inventory is shown. A slide enables to check all these information with no need to close the results or summary window.

#### 4) Alternative Summary

This section provides a summary of the basic parameters of the chosen configuration split in different categories (Figure 4.19): final quality of treated water, final quality of biosolids obtained, other technical parameters, summary of the two cost-benefit analysis, summary of the outcome in the life cycle analysis and an overall mark obtained through the multicriteria analysis.

Finally, in this summary screen, there 3 buttons can be found:


**SAVE:** This will save the session, saving all the introduced inputs during the scenario definition, enabling the end-user to check out later the configurations obtained.

**PRINT:** You can print in a more readable form the basic data of the selected option.

**GO TO SIMULATION:** The ultimate goal of the EDSS is to choose configuration that could be sent to a simulation program where you can refine, study and predict the exact behavior of the configuration chosen. At the moment, this option is not yet available.

**Figure 4.19.** Screen capture of the section Alternative Summary.

### 4.3.2 Decision Support Complementary tools

As shown in Chapter 4, the initial software menu is characterized by 5 main different sections. Although sections in the right part of the lobby are not directly involved in the operation methodology their extra capabilities can provide helpful support to end-users and improve the decision-maker experience. The set of available complementary capabilities are: a) **4.3.2.1 Scenario management**; b) **4.3.2.2 Libraries**; and c) **4.3.3.3 NOVEDAR technologies**.

#### 4.3.2.1 Scenario management

This section allows a clear interface to open previously saved sessions (Figure 4.20). Using this saved sessions the user does not have to enter again the information for a particular scenario. Therefore, this section enables to modify the data and the priority given to different criteria in specific scenarios and see how different treatment options changes depending on such modifications. In the same section is expected to add a selection area where they appear the most recent sessions and user-highlighted.

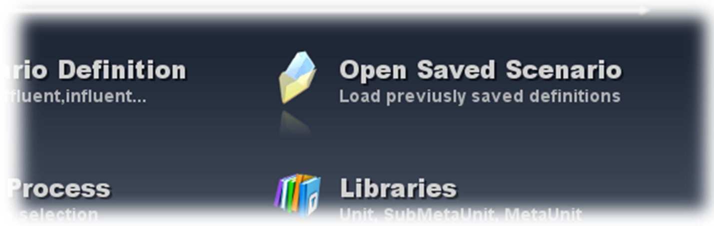


**Figure 4.20.** Snapshots of the lobby focused at the Scenario management section

### 4.3.2.2 Libraries

Libraries represent (Figures 4.20 and 4.21) a direct access to all the information categorized and related to the different technologies that are incorporated to EDSS. All the knowledge collected and comprised within the aforementioned knowledge bases can be always retrieved, check out and consulted through the "Libraries" section. Each technology has its corresponding set of tabs where the information about different aspects and specification is shown. Tabs are categorized as in the Knowledge acquisition chapter, and an extra tab showing the technology compatibilities is also provided.

Moreover, all knowledge incorporated in KBs is always referenced; highlighting the exact knowledge source from where it was retrieved. Furthermore, exists the chance that all existent default values can be modified by the user in order to adapt them to specific user experience and project or decision-maker needs.


**Figure 4.21.** Snapshots of the lobby zoomed at the Libraries section.

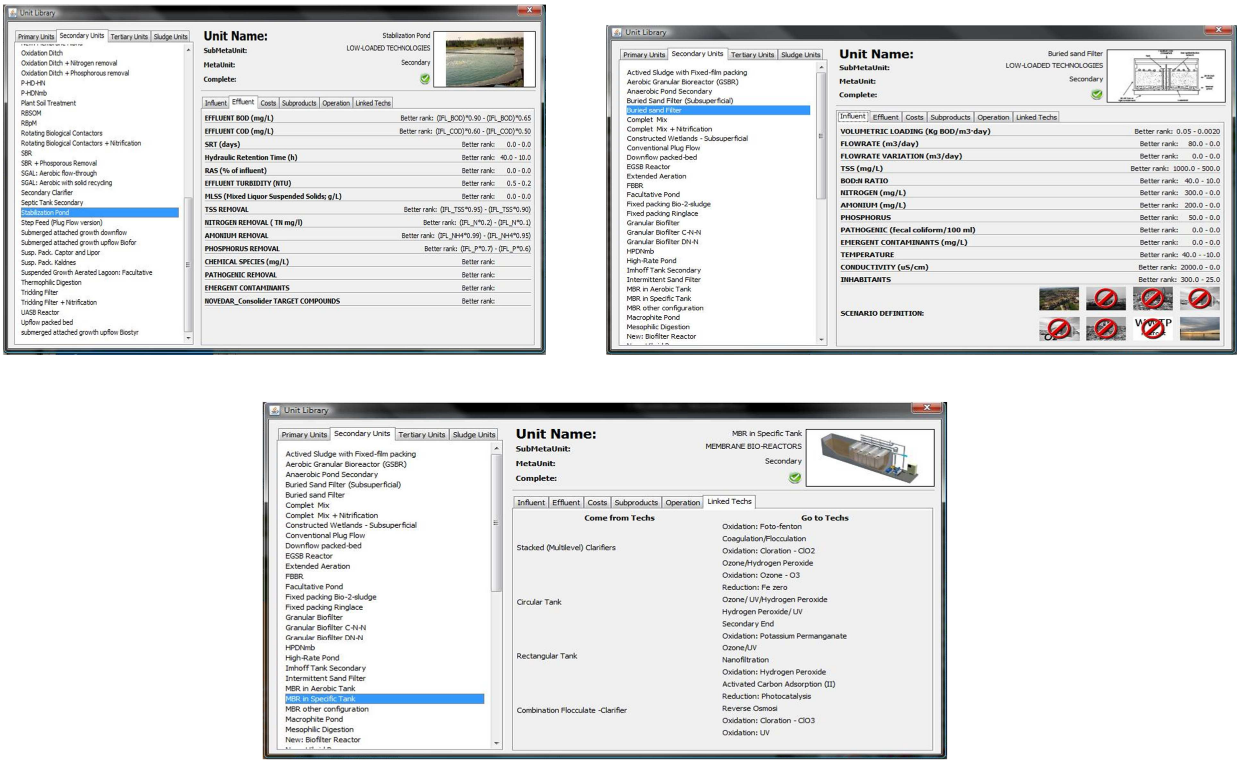


**Figure 4.22.** Screen captures of some libraries tabs.

### 4.3.2.3 NOVEDAR technologies

At last, as a show-window (Figure 4.21) of the main NOVEDAR contributions in the wastewater treatment sector, this section seeks to prioritize the knowledge of the technologies that are being developed and optimized within the group Novedar_Consolider. By clicking on the images the user can have direct access to the information contained in the library of these technologies.


**Figure 4.23.** Screen captures showing the main wastewater treatments technologies involved in the NOVEDAR project.

# Block IV

## Results and discussion of the NOVEDAR_EDSS

**PhD THESIS**

**This chapter is presented as a collection of manuscripts published as:**

**M. Garrido-Baserba**, A. Hospido, M. T. Moreira, R. Reif, G. Feijoo and M. Poch (2012). *Including the environmental vector when selecting a wastewater treatment plant*. Submitted to Environmental Modelling and Software.

M. Molinos-Senante, **M. Garrido-Baserba**, R. Reif, F. Hernández-Sancho and M. Poch (2012). *Assessment of wastewater treatment plants design for small communities: Environmental and economic aspects*. Sci. Total Environ. 427-428, 11-18.

**M. Garrido-Baserba**, R. Reif, L. Larrea and M. Poch (2012). *New Tool for the Integrated Assessment and Selection of Innovative Wastewater Treatment Technologies for Nutrient Removal.* Submitted to Environmental Science and Technology

**M.Garrido**, A. Hospido, R. Reif, M. T. Moreira, G. Feijoo, M. Poch. *An innovative tool for wastewater treatment alternatives selection integrating knowledge-based methodologies and life cycle assessment*. Poster contribution of the IWA 9th Leading-Edge Conference on Water and Wastewater Technologies (LET2012). Brisbane, Australia. 2012.

M. Molinos-Senante, **M.Garrido**, R. Reif, F. Hernandez, M. Poch. *Decision Support System to Select WWTPs Technologies for Small Populations: Environmental and Economic Assessment*. Proceedings of the EcoSTP. Specialised IWA Conference on Ecotechnologies for Wastewater Treatment. Technical, Environmental and Economic Challenges (EcoSTP). Santiago de Compostela, Spain. 2012

R. Reif, **M.Garrido**, M. Poch. *IEDSS as a Tool for the Integrated Assessment of Conventional and Innovative Wastewater Treatment Technologies for Nutrient Removal.* Proceedings of the International Congress of Environmental Modeling and Software (EMSS2010) - Intelligent Environmental Decision Support Systems. Leipzig, Germany. 2012.

# Chapter 5

## Including the environmental vector when selecting a wastewater treatment plant

*This chapter presents the development, implementation and validation of an innovative methodology for the WWTP alternatives assessment at conceptual level using a Life Cycle Analysis module. LCA considerations at this level are of the upmost importance towards the identification and assessment of real and global impacts of our existing wastewater treatment plants.*

# Chapter 5: Including the environmental vector when selecting a wastewater treatment plant

## 1. Introduction

Environmental protection, social and economic developments constitute the basis of sustainability (UCN, 2006), and may not exist other human activity more closely linked to them as wastewater treatment plants (WWTPs). Society is requiring that current wastewater treatment maximize the accomplishment of these three aspects in order to be considered sustainable (Balkema et al., 2002). To date, WWTPs have been usually evaluated by end-of-pipe approaches: so, their capability to remove the main contaminant contributors of the eutrophication in aquatics sources and ecosystems extolled them as one of the best innovations in human development. However, the application of wider sustainability criteria is essential in order to identify their real environmental impacts (Davidson et al., 2007).

Life Cycle Assessment (LCA) is a well-established procedure to quantify the environmental impacts associated with a product or process throughout its whole life cycle (ISO 2006a, ISO 2006b). LCA has been implemented in multiple areas of activities, being applied to wastewater treatment since the 1990s with different aims (Corominas et al., 2011), such as the identification of the main contributors within a specific process (Hospido et al., 2004), the comparison of different technologies/facilities (Gallego et al., 2008) or the influence of methodological aspects of the LCA tool on the evaluation (Renou et al., 2008). Regardless the particular objectives of the individual studies, the inclusion of a life cycle perspective when assessing the performance of a WWTP entails the consideration of not only the direct impacts associated to the discharge of the treated effluent (end-of-pipe approach) but also the indirect impacts associated to the inputs (materials and energy use) and outputs (emissions and waste generated) required for the treatment of the influent (holistic approach). By doing so, a complete picture of the impacts associated to the particular treatment process is provided and the transfer of environmental burdens among compartments (water, air and soil) or between impact categories (for example, eutrophication versus global warming) is detected and evaluated. The sooner this identification takes place, the better the chances /the decisions are of preventing serious environmental impacts from developing.

Decision support systems (DSSs) support a user in choosing a consistent solution for a particular problem in a reduced time frame (Poch et al., 2004). The innovative Novedar decision support system (Novedar_DSS)[2] is a tool developed for WWTPs alternatives selection which includes technical, economic and social issues and operation analysis

[2]The development of the Novedar_DSS to systematize the design of wastewater treatment plants was performed under the project "Conception of the WWTP of the XXI century”. http://www.novedar.com

(Garrido-Baserba et al., 2011). The software is composed by extensive databases (legislation, fully characterization of WWTP-related technologies, compatibility tables, etc.) and methodologies such as Multi-Criteria Analysis (MCA) and Cost-Benefit analysis (CBA). The DSS enables to systematize the design of wastewater treatment plants and provide specialized support during the decision-making process through an interface where users can extract all the required information in order to improve the quality of their decisions.

The range of applications of DSSs in water treatment problems is overwhelming (Hamouda et al., 2009); issues include selection and design of treatment processes (Benedetti et al., 2008; Comas et al., 2004; Rodriguez-Roda et al., 2000; Vidal et al., 2002) sequencing of selected processes either in parallel or in series in a treatment trains (Joksimovic et al., 2006), and monitoring and control of treatment plants. (Evenson and Baetz, 1994; Hidalgo et al., 2007; Rodriguez-Roda et al., 2002; Turon et al., 2007) or even, for implementing control and operation strategies (Flores-Alsina et al., 2010; Turon et al., 2009; Wotawa et al., 2010). Nevertheless, the development of software which integrates process synthesis, MCA, CBA and LCA methodologies constitute a pioneer approach and the main highlight of this work, since it clearly overcomes limitations still present in available DSSs.

By the joint application of LCA and DSS, this study aims to include the environmental vector on the decision making process when selecting a possible flow-diagram for a specific wastewater management scenario. So far, the only environmental criterion applied was the accomplishment of the required treated water quality depending on the final discharge or reuse. Going further, this study describes how the implementation of the environmental life cycle thinking took place and presents its application to a set of Spanish WWTPs.

## 2. Materials and methods

### *2.1. Decision Support System*

DSS are gaining interest within the wastewater management sector (Hamouda et al., 2009). A DSS is an information system that supports a user in choosing a consistent, near optimum solution for a particular problem in a reduced time frame (Poch et al., 2004). They can be used to justify multi-criteria decisions of policy-makers (transparency) more than making real decisions, and provide to end-users a tool to play with "what-if" scenarios, to explore the response surface and the stability of the solution in order to improve the consistency and quality of decisions (Alemany et al., 2005; Comas et al., 2004; Cortés et al., 2005; McIntosh et al., 20011). DSSs are inherently integrated (statistical/numerical methods, environmental ontologies, etc.), usually consisting of various coupled models, databases, and assessment tools capable of supporting complex decision making processes through an accessible computer interface that presents results in a readily understandable form (Huang et al., 2010; Matthies et al., 2007; Shim et al., 2002).

The DSS applied in this study is the Novedar_DSS (Figure 1), and has been already applied successfully for selection of feasible WWTPs (Garrido-Baserba et al., 2011), including also the consideration of economic parameters (Molinos-Senante et al., 2012). A variety of sources were used for the development of the different data bases, which comprise knowledge extracted from specialized literature and from interviews with experts within the Novedar Project. The proposed model for the DSS is based on a hierarchical decision approach combined with a knowledge-based system, which uses the interaction of different main knowledge bases (KBs) in order to provide the required optimum alternatives. Further information about the development of the Novedar_DSS can be found at (Garrido-Baserba et al., 2010).


**Fig.1.** Snapshots of the scenario definition tabs: Menu, Discharge/Reuse and Sludge Management

### *2.2 LCA Implementation*

The LCA methodology comprises four stages (ISO 2006a): i) goal and scope definition, where the product/process/activity to be studied and the purpose of the study are decided; ii) life cycle inventory (LCI), where the energy carriers and raw material used, the emissions to atmosphere, water and soil, are quantified; iii) life cycle impact assessment (LCIA), where the LCI is transformed into impact categories to better understand the environmental significance of the system under study; and iv) interpretation of results, where conclusions and recommendations are drawn.

#### 2.2.1 Goal and scope definition

The general goal of this study is the inclusion of the environmental vector on the decision making process when selecting the most appropriate process flow diagram (PFD) for a particular scenario.

The functional unit (FU) defines the quantification of the function(s) of the process under study and its primary purpose is to provide a reference to which the input and output data are related (ISO, 2006a). When defining the FU of a WWTP, different choices are possible and in this study it has been defined in terms of the volume of treated water ($m^3$) during a certain period of time, similarly to other research works (Rodriguez-Garcia et al., 2011a and Suh and Rousseaux, 2001)

The system under study is limited by its system boundaries and all unit processes studied are within these boundaries. Our assessment considers the environmental impact associated with the operation of the water line (i.e. operation of primary, secondary, and tertiary treatments (when available) and final discharge of the treated effluent) as well as the sludge line (i.e. treatment and final disposal), excluding therefore the stages of plant building and demolishing, reported as less relevant (Corominas et al., 2011).

### 2.2.2 Life cycle inventory

The elements to be measured for the creation of the inventory data within the DSS model (Table 1) were defined on the basis of previous studies (Hospido et al., 2004; Hospido et al., 2008; Rodriguez-Garcia et al., 2011a) as well as on the parameters provided by the internal set of KBs built-in the DSS. The knowledge bases contain information about the different technologies comprising the different wastewater treatment schemes as well as their environmental, economic, technical or legal specifications and requirements. Thus, each typology of technology encapsulates a wide set of data (removal efficiencies, operational parameters, space requirements, sludge production, etc.) defined by mechanistic/empirical equations, enabling the simulation in steady-state. Coincident elements with the inventory were directly taken into account (such as energy use, polyelectrolyte and other chemicals consumption, biogas produced…). Parameters which were not implemented in DSS (such as phosphate leakage or avoided production of fertilizers due to the sludge application on agricultural soil) were incorporated to the KBs framework following the procedures described in Rodriguez-Garcia et al. (2011a).

**Table 1.** Elements selected for the inventory of WWTP, all data is presented for FU ($m^3$)

| Parameter | Unit |
|---|---|
| Energy use: | |
| Electricity from the grid | kWh |
| Chemicals consumption: | |
| Methanol ($CH_3OH$) | g |
| Iron chloride ($FeCl_3$) | g |
| Polyelectrolyte | g |
| Other background processes: | |
| Transport | kg·km |
| Sludge management | kg ww* |
| Other solids management | kg |
| Avoided products [(1)]: | |
| N as fertilizer | g |
| $P_2O_5$ as fertilizer | g |
| Direct emissions: | |
| Total nitrogen (Nt) to water [(2)] | g |
| Total phosphorous (Pt) to water [(2)] | g |
| Chemical Oxygen Demand (COD) to water [(2)] | g |
| $PO_4^{3-}$ to water [(1)] | g |
| $NH_3$ to air [(1)] | g |
| $N_2O$ to air [(1)] | g |

[(1)] Associated to the application of sludge to agricultural land
[(2)] Associated to the discharge of treated water
* ww = wet weight

2.2.3. Life cycle impact assessment

Two indicators were selected for the evaluation of the environmental burdens associated to a particular WWTP:

c) Eutrophication Potential (EP): This impact category has been considered the most relevant environmental issue in the majority of published LCAs on WWTPs (Corominas et al., 2011 and Lassaux et al., 2007).
d) Global Warming Potential (GWP). Even when it is not among the most relevant impact categories for WWTPs (Larsen et al. 2007), GWP is usually regarded as a significant environmental problem worldwide (UN, 2010) .

Both environmental indicators have been quantified by means of the CML[3] 2001 v2.5 method (Guinée et al., 2002), which converts all eutrophying substances to $PO_4^{3-}$ equivalent (Table 2) and all the greenhouse gases emissions into $CO_2$ equivalent (Table 3).

[3] CML 2001 is a LCA methodology developed by the Centre of Environmental Science (CML) of Leiden University in the Netherlands (http://cml.leiden.edu/software/data-cmlia.html)

**Table 2.** Characterization factors used for EP for selected substances emitted to water

| Substance | Eutrophication Potential ($kg\ PO_4^{3-}$ eq./kg substance) |
|---|---|
| Chemical Organic Demand (COD) | 0.022 |
| Nitrogen, total (Nt) | 0.42 |
| Phosphorous, total (Pt) | 3.06 |
| Phosphate | 1 |

**Table 3.** Characterization factors used for GWP for selected substances emitted to air

| Substance | Global Warming Potential ($kg\ CO_2$ eq./kg substance) |
|---|---|
| Carbon dioxide, fossil | 1 |
| Carbon dioxide, biogenic | 0 |
| Methane, fossil | 23 |
| Methane, biogenic | 20 |
| Dinitrogen monoxide | 296 |

In addition to those characterization factors (Tables 2 and 3), emission factors are also required in other to include the production processes associated to the individual elements of the inventory. To do so, the Ecoinvent database v 2.2 was used.

**Table 4.** Background processes selected from the Ecoinvent database and corresponding emission factors for the two impact categories under study.

| **Inventory parameter** | **Ecoinvent process** | ***Unit*** | ***EP kg $PO_4^{3-}$ eq/unit*** | ***GWP kg $CO_2$ eq./unit*** |
|---|---|---|---|---|
| **Electricity** | Electricity, low voltage, at grid/ES | *kWh* | 0.00115 | 0.591 |
| **Methanol** | Methanol, at plant/GLO | *Kg* | 0.000408 | 0.736 |
| **Iron Chloride (III)** | Iron (III) chloride, 40% in $H_2O$, at plant/CH | *Kg* | 0.00291 | 0.801 |
| **Polyelectrolyte** | Acrylonitrile from Sohio process, at plant/RER | *Kg* | 0.00831 | 3.02 |
| **Transport** | Transport, Lorry 3.5-7.5t EURO5/RER | *Tn/km* | 0.000385 | 0.472 |
| **Sludge disposal: landfill** | Disposal, municipal solid waste, 22.9% water, to sanitary landfill/CH S | *kg ww** | 0.0025 | 0.455 |

| | | | | |
|---|---|---|---|---|
| **Sludge disposal: land application** | Application, Slurry spreading, by vacuum tanker , covered/CH | *kg ww* | 0.00000217 | 0.00121 |
| **Sludge disposal: incineration** | Disposal, raw sewage sludge, to municipal incineration/CH | *kg ww* | 0.000416 | 0.0131 |
| **Solids disposal** | Disposal, inert waste, 5% water, to inert material landfill/CH | *Kg* | 0.0000103 | 0.00709 |
| **N-based fertilizer** | Ammonium sulphate, as N, at regional storehouse/RER | *Kg* | 0.0029 | 2.79 |
| **P-based fertiliser** | Diammonium phosphate, as $P_2O_5$, at regional storehouse/RER | *kg* | 0.0552 | 1.57 |

* ww = wet weight

### 2.2.4 Interpretation of results

The process of assessing the results so as to draw conclusions is the fourth and final stage of an LCA study.

### *2.3 Validation of the implementation of the environmental indicators*

The selected plants used as a validation tool were previously inventoried and assessed by (Rodriguez-Garcia et al., 2011a), which reported data from 24 WWTPs designed for populations larger than 50,000 inhabitants. The facilities were there classified into 5 typologies according to the quality requirements set in the European urban wastewater directive (EEC, 1991) and the Spanish legislation concerning water reuse (MP, 2007). Three different secondary treatments were considered, being the most widely used the conventional activated sludge (CAS) process (18 facilities), while extended aeration (EA) was used in three facilities and only one used the oxidation ditch (OD).

The first step was the data entry process in which the scenario specifications for each plant (Table 5) were introduced in the DSS through a set of interface screens (Fig.1). Afterwards, the knowledge-based system generated the associated inventory. For each particular scenario, the different alternatives generated by the DSS were ranked according to a default weight defined in the multi-criteria parameters (i.e. technological, operational, economic and environmental criteria). Next, a pre-selection of the specific wastewater treatments alternatives to match with the technological set composing the real plants was fulfilled. Therefore, the most similar PFD and same secondary treatment alternative (CAS, EA and OD) to the real facility were always considered.

**Table 5.** Parameters required during the data entry process to characterize the facilities.

| Initial Conditions Topic | Parameters |
|---|---|
| **Community and influent characteristics** | · PE (people equivalent)<br>· Number of inhabitants (year X and X-1)<br>· Flow rate<br>· TSS (Total Suspended Solids)<br>· COD (Chemical Oxygen Demand)<br>· BOD (Biological Oxygen Demand)<br>· Total Nitrogen (Nt)<br>· Total Phosphorous (Pt)<br>· Conductivity |
| **Receiving media** | · River discharge (sensitive or not sensitive |
| **Treated water destination** | · Applicable Legislation (Reuse typology)<br>· Percentage for reuse purposes or discharge |
| **Sludge waste destination** | · Agricultural, composting, landfill, valorisation or incineration<br>· Distance between the WWTP and the sludge disposal option |
| **Process flow diagram** | · Pre-treatment + Primary treatment<br>· Secondary treatment<br>· Tertiary treatment<br>· Sludge treatment<br>· Head returns treatment |

Hence, the data entry process of the 22 WWTPs computed through DSS led to an estimated inventory for each plant. Afterwards, an evaluation of the environmental impacts, applying the aforementioned emission and characterization factors, was done. Finally, these estimated impacts were compared with those measured from the work of Rodriguez, G. et al. (2011a).

The comparison is essential during the validation of the methodology approach, as the obtained results can be also used to determine if the real WWTPs were managed under efficient operational conditions.

## 3. RESULTS AND DISCUSSION

### *3.1 Inventory data: measured versus modeled values*

This section summarises the quality level of the estimations carried out by the DSS for the 22 WWTPs under study, using the real values reported from the aforementioned work of Rodriguez-Garcia et al. (2011a) as reference.

The general conclusion is that the correlation between both sets of values is high, as the estimated figures are quite similar for all elements taken into consideration (Fig. 2-5). Estimated values did not present significant differences from real plants, showing the coherence and consistency of DSS outputs with real plants values. Even, it could be stated that plants within the same typology were well-represented in the simulations. However, some differences can be found. On the one hand, in those typologies requiring stricter effluent quality, the chemical precipitation method for the removal of phosphorus had to be modified in some specific cases in order to match with real plant PFDs. Aluminum sulfate $Al_2(SO_4)_3$, the main option proposed by the DSS, was substituted by iron chloride ($FeCl_3$). On the other hand, the pre-treatment stage for solid disposal (Table 4) presented the higher differences (in some cases, up to 30% of error between the expected and the real data). The cluster of equations to predict fats (g), grit (t) and transport (kg km) had to be revised and corrected in some cases. However, the emission factor of this stage of process makes was of minor relevance after its conversion into category impact. The few discrepancies within the inventories were detected thanks to this validation process, whereas some trends in the environmental impacts could be accurately predicted previously to the conversion of such values.

Simulations showed higher pollutant removal efficiencies compared with data from real facilities, particularly for Nt. Real performance of plants is sometimes subjected to changes (weather conditions, inadequate operation, presence of toxics in the influent, etc.) which affect the quality of the final effluent. Apparently, this explanation might explain the differences observed. However, a more in-depth analysis is presented in the following section.

### *3.2 Environmental indicators: measured versus modeled values*

For the assessment of the similarities and divergences between the magnitudes of the environmental indicators obtained from the DSS and the values calculated for the real facilities, a classification of three zones was established on the basis of the parameter R:

R = Environmental indicator from DSS / Environmental indicator from real data

R = [0.75, 1.25] → High similarity, reliable validation

R = [0.50, 0.75] or [1.25, 1.50] → Low similarity, debatable validation

R = < 0.50 or > 1.50 → High divergence, unacceptable validation

For a better understanding of the results, main contributors for both categories were analyzed, highlighting that differences between estimations by the DSS and real cases might be better explained considering the appearance of different operational issues during real plants operation, rather than low-quality predictions done by the DSS approach.

*3.2.1 Eutrophication potential*

Figure 2 reports the values of the parameter R related to the first environmental indicator (EP) for the 22 facilities evaluated. According to the results obtained, more than 35% of the plants achieved a good validation (error < 25%), around 18% a moderate validation and the biggest group (10 out of 22) reported a poor correspondence (error > 50%).

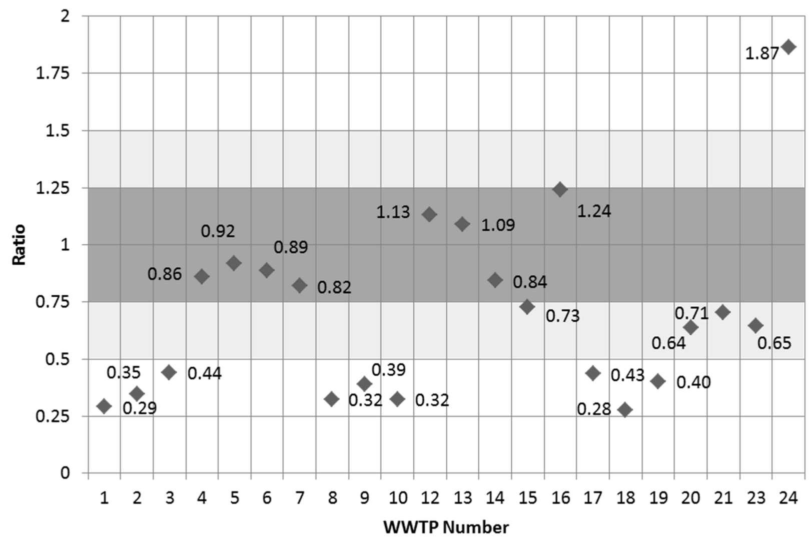


**Figure 2.** Correlation ratio (R) for eutrophication potential.

Ratio values below 1, where the majority of the plants are located (18 out of 22), indicate that simulated WWTPs resulted in lower associated impacts than measured plants. The reason behind this behavior is, as previously stated on the inventory analysis, that the estimated plants appear to have higher removal efficiencies than real facilities, and such differences in the effluent quality have a significant influence on the EP result as this indicator is clearly dominated by the direct release of nutrients to the environment (Fig.3).

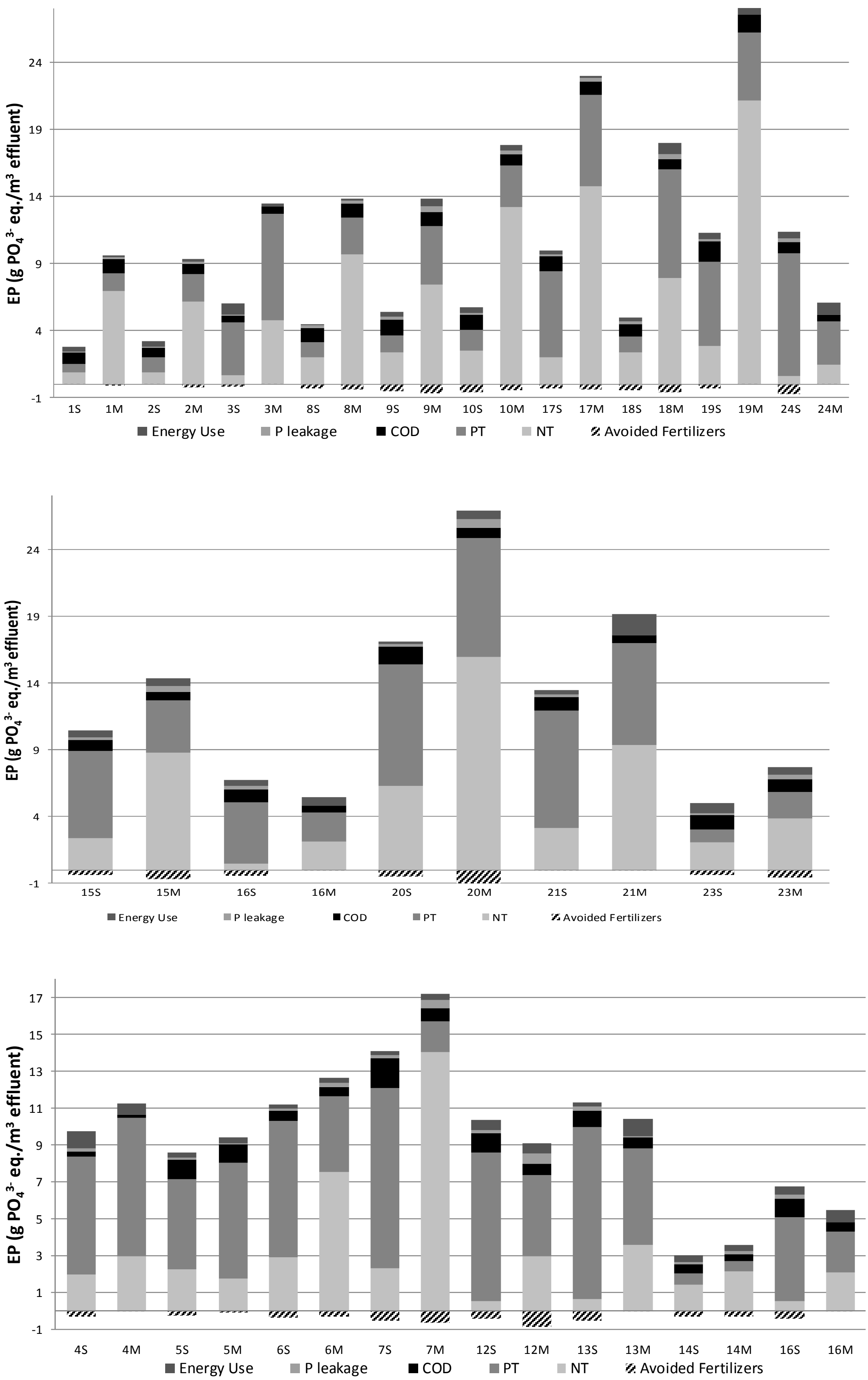


**Figure 3.** Eutrophication potential (kg $PO_4^{3-}$ eq. /$m^3$ treated effluent) for the WWTPs (M=Measured vs. S=Simulated) with **a)** R < 0.50 or > 1.50; **b)** R = [0.50, 0.75] or [1.25, 1.50], and **c)** R = [0.75, 1.25].

When analyzing the individual contributors in details, the relevance of the direct emissions of nitrogen (measured as Nt) is clear (Fig. 3). A poor comparison (Fig. 3a) is found in those plants where reported nitrogen removal efficiencies (which varied from 15% to 54%) were significantly lower than those implemented in the DSS (i.e. gathered from literature and experts interviews). As data from real plants corresponds to an average of one year, it could not be considered that these low or unexpected values are due to extraordinary conditions, as mentioned before. Only plants 1, 2 and 3 might reveal some biases in the LCA estimations corresponding to a climatologically different region (Rodriguez-Garcia et al., 2011b), characterized by intense rainfall events which might have contributed to these predictions.

Fig. 3b shows the lower number of facilities. In this case, the correspondence was moderate, although the discrepancies observed can be attributed to similar factors than the mentioned for Fig. 3a. Finally, Fig. 3c displays those facilities that reported the higher values for parameter R. In this case, even when the contribution of the impact elements is properly predicted and their magnitude order is maintained in almost all the plants, high differences regarding the P contribution are present (which is more related to its high characterization factor than to real differences on the P simulated and real values). In several facilities (for example: plants 6, 7, 13 and 16), the overestimation of the P-related impact is balanced by an underestimation of the N removal achieved and therefore the total value is similar (for simulated and real conditions) although the distribution of the impacts is different.

However, a thorough interpretation of the results should be considered. Plants with lower efficiencies than those provided from both literature and the considered well-operated facilities could be considered as not representative. The worst ranked plants, with ratios far distanced from 1 should be discarded from this type of study as they do not represent the current performance of this plant typology (CAS), and, thus, there would be no sense in proposing such alternative if their potential capabilities are underestimated. By doing so, more than the 95% of the plants would match satisfactorily with the DSS estimations. Hence, it could be stated that the reliability of the approach to predict the EP would be increased from 53% to an approximate 95%.

Nevertheless, if variability in the operational conditions wants to be kept in such studies, a second option would be the implementation in the DSS of two differentiated ways to operate facilities within the same typology, those well-operated and those whose operation typically present limitations and issued, and thus, poorer performance. In the other hand, it is important to remark that the Novedar_DSS allows a transparent modification and update of the implemented efficiency equations. Thus, default efficiencies could be modified by the expert user to fit within its own knowledge and experience.

*3.2.2 Global warming potential*

When the GWP is evaluated, the values of the parameter R tend to be closer to 1 (Fig. 4) and, in fact, the previously observed trend of overestimating the EP impact associated to the plants is not revealed for GWP. According to the results, the 50% (11 out to 22) of the plants achieved a reliable correspondence, around 18% were kept in the confident zone, and 32% was found in the poor correspondence zone (but note that 3 of the 7 plants are located in the border with values very close to those of the confident zone). WWTPs significantly distanced from the acceptable validation zone at R>1.50 (WWTP 1, 2 and 3) were previously pointed out as bad-operated and hence, the discard of these WWTPs underperforming their real capabilities leads to a close 98% of the DSS estimations reliability.

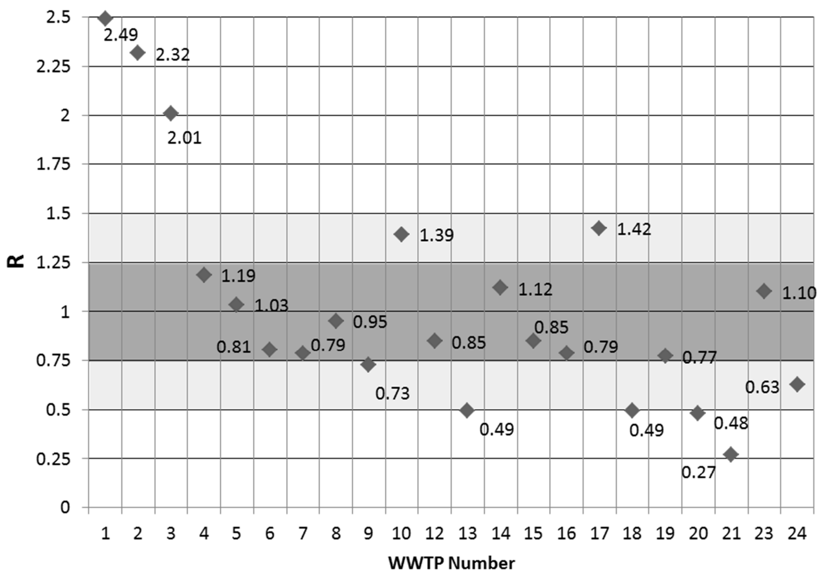


**Figure 4.** Correlation ratio (R) for global warming potential.

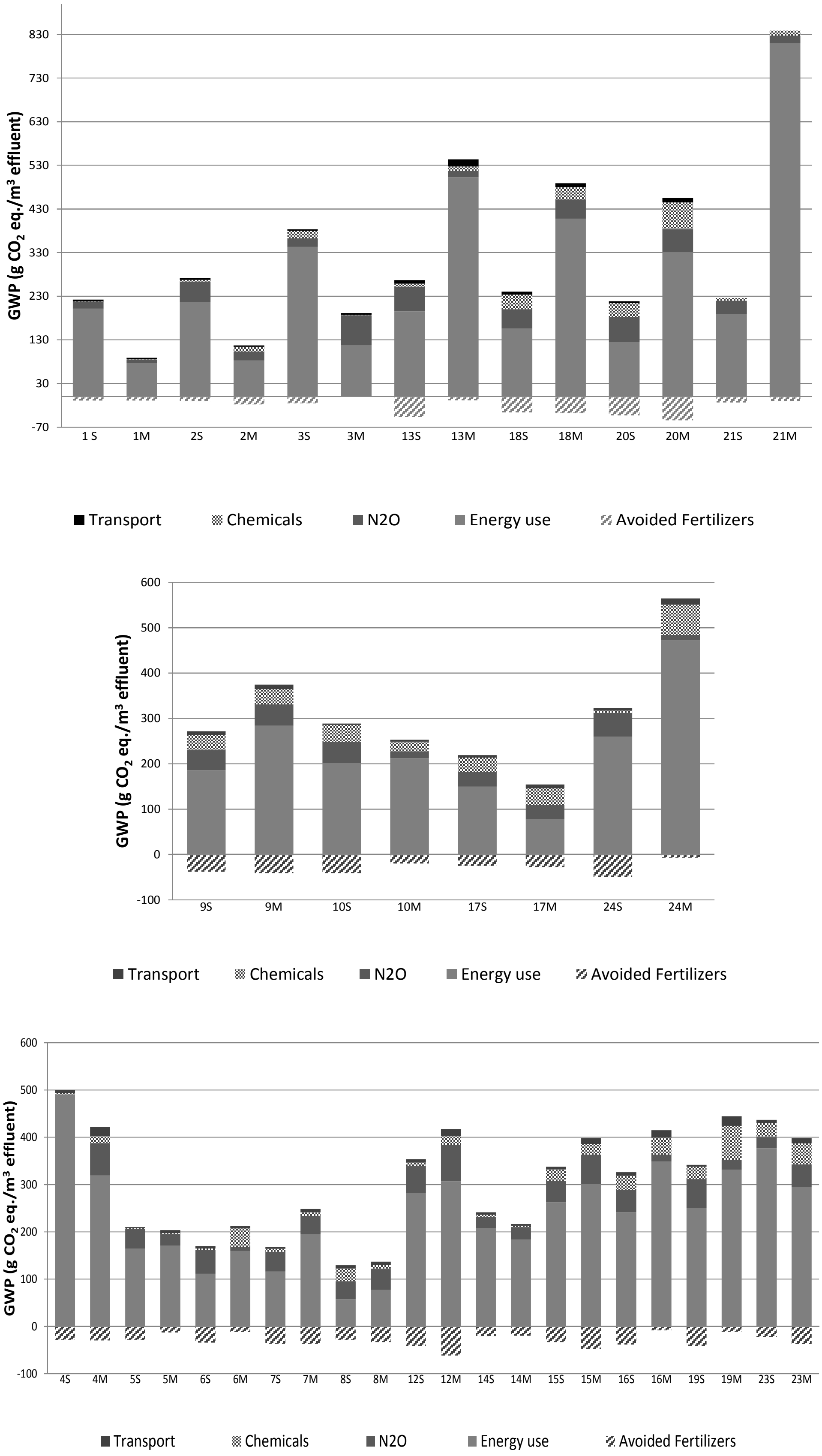


**Figure 5.** Global warming potential (kg $CO_2$ eq. /m3 treated effluent) for the WWTPs (M=Measured vs. S=Simulated) with a) R < 0.50 or > 1.50; b) R = [0.50, 0.75] or [1.25, 1.50], and c) R = [0.75, 1.25].

Facilities reporting a poor correspondence on the validation (error >50%) are shown in Fig. 5.a, whereas the WWTPs within the confident zone are grouped in Fig. 5.b. As expected, energy use dominates in all cases this second environmental indicator, mainly due to the $CO_2$ emissions from fossil fuels (i.e. item energy use).

Focusing on the plants with worst R parameter (Fig. 5.a) we can see a divergent behavior regarding measured versus modeled energy use values. So, on the one hand an unusual low energy use was found for WWTPs 1 and 2, with measured values far from the figures normally reported in literature (from 0.1-0.2 $kWh/m^3$), which could be directly related to the low nutrient removal efficiencies already mentioned for those plants (see Figure 3a): a lack of aeration in the reactor basin implies a relevant saving in the energy use whereas the nitrification process, which demands more oxygen, has to be necessarily affected. On the other hand, WWTP 21 (Fig. 5a) reported an energy use (1.37 $kWh/m^3$) that doubles the values normally reported for well-operated plants (CEDEX, 2009; Gallego et al., 2008; Hernandez-Sancho et al., 2011; Ortega de Ferrer et al., 2011; Pasqualino et al., 2011; Tchobanoglous et al., 2003) and that is even substantially higher than those requiring tertiary treatments. Since higher impacts in GWP are directly related with the increasing complexity of the technology applied, mainly associated with larger consumption of electricity and chemicals (Beavis and Lundie, 2003; Clauson Kaas et al., 2006; Rodriguez-Garcia et al., 2011b), different reasons might explain this particular data, related with technical issues in the functioning of more expensive membrane-based systems. It is important to remark that the stricter water quality standards have to be accomplished in the reuse typology. Although WWTP 21 was already expected to have higher energy consumption due its reuse typology, the real value is far from the expected (lower than 0.9 -1.1$kWh/m^3$). Better estimation could be done by the identification of specific process flow diagram of the plant. On-going research should identify the real plant diagram and possible failures in order to check if really exists such mismatching.

Fig. 5.b, on the other hand, shows the plants within the confident validation zone. Divergences in the energy use predictions are still here the dominant contributor to low R values. Only plant 24 presents a significant bias in the chemical consumption that further confirm its belonging in this rank, mainly due to the differences in theoretical methanol consumption that the DSS estimate necessary for the influent characteristic of this specific plant in order to accomplish its reuse typology objective. Regarding Fig. 5c, the contribution of the impact elements is properly predicted and the discrepancies observed can be attributed to similar factors, although with significantly lower magnitude. Some cases as WWTP 6 and 19 their matching improved due inventory differences in chemical consumption (high consumption of $FeCl_3$ in measured inventory). Such differences assured their position in the reliability validation rank.

Moreover, differences in the estimated and measured energy use can be interpreted as the potential for minimizing the environmental impact of real plants. For plants with R values closer to 1, operational performance can be considered optimum, leaving few chances for improving the environmental performance. Nevertheless, our approach permits to assess operational and environmental prediction of scale-ups. Thus, this technique can be useful to identify, at a conceptual stage, performance trends or theoretical potential impacts once the pilot plants are being scaled-up. Also, the results estimated for the whole set of plants highlight the fact that energy use, chemical consumption and air emissions might be optimized in real plants in order to guarantee a net improvement in operational efficiency and environmental performance. In this sense, the DSS estimations constitute a useful tool in order to gain knowledge about the degree of optimization that any typology of plant could reach, either increasing economic gains by, for example, increasing biogas production or reducing environmental impacts.

The reliability of the methodological approach for the three technology typologies presented in the set of WWTPs (i.e. CAS, OD and EA) seems to confirm this trend. When considering separately the different typologies, it can be seen that the oxidation ditch presented lower aeration requirements than the predicted. However, the total ratio was kept at $R > 0.50$ or $< 1.50$. Moreover, extended aeration presents a very similar energy use for both measured and simulated. Regardless of the treated water destination, the DSS seemed to estimate correctly the different outputs for the three technologies considered.

## 4. CONCLUSIONS AND FUTURE OUTLOOK

The inclusion of the environmental vector by means of a LCA perspective within a DSS has been described and proven, in a limited set of WWTPs, to be an adequate way of improving the decision-making process during the WWTP alternative selection.

The validation done showed that a high percentage of the WWTPs (55% and 82%) were found to match with DSS predictions with an error ratio lower than 0.5 in both categories analyzed (EP and GWP). A further detailed analysis suggested that previous percentages could increase to 90-95% when non-optimized WWTPs were discarded from the analysis. Therefore, the present study allowed the identification of the best and the worst-predicted treatment plants in order to appoint optimized plants and, at the same time, highlighting the weaknesses and strengths of this approach. The environmental characterization of WWTPs and their respective simulations led to propose environmental reference values for the respective technological typologies.

The simulations computed for the WWTPs resulted, in almost all the cases, in lower values for the EP indicator. Environmental reductions ranging from 25% to 40% were estimated due to the fact that theoretical predictions overestimate the real removal efficiencies of the plants evaluated. EP results suffer from strong variations between facilities, even when they operated with the same treatment typology (CAS). Main differences are inferred from the high standard deviations observed in the nitrogen removal efficiencies. Measured differences between the same typology provide greater uncertainty than DSS estimations.

The GWP reliability for the three technology typologies included (CAS, OD and EA) was probed, with an average matching in the considered well-operated plants closely to 98%. The parameter energy use dominates the GWP category, and represented the main contributor of the favorable matching detected between measured and estimated plants. Thus, the favorable predictions carried out by the DSS in such parameter implied the observed broad correspondence in this environmental indicator.

The most accurate assessment of the sustainability of different treatment technologies must comply with environmental, social and economic needs in order to cope with the three dimensions of sustainability. This chapter constitutes a pioneer approach for implementing an efficient and effective tool to detect potential environmental impacts, also contributing to the decision-making processes of suitable alternatives which incorporate the environmental vector according to the sustainability paradigm.

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# Chapter 6

## ASSESSMENT OF WWTPs: TECHNICAL AND ECONOMIC ASPECTS.

*This chapter presents the implementation of two economic methodologies to support the economic assessment of WWTP at conceptual level. The application of this economic and technical module in the DSS enable the study of feasibility from an integrative point of view (economic, environmental, technical and social) of the most popular technologies applied for small populations (SWWTs).*

# <u>Chapter 6</u>: Assessment of wastewater treatment plants design for small populations: Technical and economic aspects

## 1. INTRODUCTION

Many countries are facing important challenges in the field of water management. Satisfying an increasing demand of water resources while avoiding the degradation of ecosystems constitutes a complex challenge that requires viable answers following economic, social and environmental criteria (Macleod & Haygarth, 2010). Although the level of knowledge available to decision-makers to cope with drought and quality degradation is becoming increasingly sophisticated, water scarcity is being intensified in a parallel manner in nearly all basins and water policies have necessarily to be improved.

The European Directive 91/271/EEC (UWWTD) states that all generated wastewater agglomerations of between 2,000 and 10,000 people equivalent (p.e.) must set up collection and treatment systems by December 2005. Therefore, one of the main challenges for European authorities for the achievement of the good ecological status of water bodies, is to implement the appropriate treatment of wastewater in small agglomerations.

For example, Spain is characterized by the existence of a huge amount of low-populated locations. In fact, more of 73% of the municipalities have less than 2,000 inhabitants, stating for almost 7% of the population of the country (INE, 2011) and the non-treated load of sewage originated in such small agglomerations is about 3-4 million p.e. (Salas et al., 2011). According to the Spanish National Plan for Water Quality (NPQW), which devotes special attention to the treatment of wastewater in such agglomerations, 100% of treated sewage must be achieved by 2015 (Aragón et al., 2011).

In addition, EU Commission has to come to the conclusion that additional sensitive areas and their related catchments should be designated. This fact entails the need of upgrading the treatment applied for a significant number of discharges and the development of new facilities in the near future. In this context, it is crucial to find out the most feasible technologies from an integrative point of view to tackle with new wastewater management projects, depending on each specific scenario.

The selection of the most suitable process flow diagram involves many possible options and elements which are all linked, giving multiple interactions and a very large number of design and operation combinations. The accomplishment of a variety of objectives (such as effluent requirements, local conditions, investment costs, environmental issues, operational costs, etc.) and multiple criteria also increases the complexity of the problem, such that selection of the most appropriate plant design becomes a very difficult task (Flores-Alsina et al., 2010; Poch et al., 2004).

In that sense, recent years have seen the arising of promising tools able to cope with that level of complexity, the so called Environmental Decision Support Systems (EDSS). EDSS are tools designed to confront with this multidisciplinary nature and therefore to deal with complex environmental problems. They are inherently integrated (statistical/numerical methods, environmental ontologies, etc.), and consist of various coupled models, databases, and assessment tools capable of supporting complex decision making processes (Shim et al., 2002; Matthies et al., 2007; Huang et al., 2010). Therefore, EDSS are gaining interest within the wastewater management sector. They can be used to justify multi-criteria decisions of policy-makers (transparency) more than making real decisions, and provide to end-users a tool to play with "what-if" scenarios, to explore the response surface and the stability of the solution in order to improve the consistency and quality of decisions (McIntosh et al., 2011)

Previous experiences successfully applied EDSS tools to identify adequate wastewater treatment technologies for small communities (Alemany et al., 2005; Comas et al., 2004). However, taken into account the role assigned by the WFD to water planning, suitable methodological approaches regarding the economic valuation of the different proposed alternatives by the EDSS were not sufficiently addressed. In this context, among the number of methodologies available which can be used as support instruments for the decision makers, cost-benefit analysis (CBA) is nowadays between the most accepted (Molinos-Senante et al., 2011). In this sense, according to WFD, the environmental benefits derived from implementing measures or projects should be included in feasibility studies. Because these benefits are difficult to calculate since they are not determined by the market, economics have made important efforts in order to estimate the monetary value of them (Garrod & Willis, 1999; Glover, 2010). In the specific context of wastewater treatment, Hernández-Sancho et al., (2010) have adapted the pioneering methodology developed by Färe et al., (1993) in order to quantify in economic terms the environmental benefits derived from wastewater treatment.

The EDSS presented in this chapter (NOVEDAR_EDSS) constitutes a pioneer approach for implementing efficient and effective policies and strategies for wastewater treatment since it integrates not only the traditional methodology for the economic assessment of the technologies based on investment and operating costs but also provides an economic feasibility indicator which includes the economic value of the environmental benefits from wastewater treatment.

The aim of the study presented here is assess ten different technologies (Table 1) set-up for the secondary or main treatment step in small WWTPs, in order to establish which ones might be more adequate from an integrative point of view embracing economical and environmental issues. In doing so, nine scenarios regarding influent load and water reuse options are evaluated. The most relevant factors contributing to the overall plant feasibility and environmental impact will be identified and discussed.

## 2. MATERIALS AND METHODS

### 2.1. NOVEDAR_EDSS

The development of the NOVEDAR_EDSS to systematize the design of wastewater treatment plants is performed under the project "Conception of the WWTP of the XXI century”. NOVEDAR_EDSS is innovative software for WWTP design which includes environmental, economic and social issues and operation analysis. The software includes several extensive databases (legislation, fully characterization of WWTP-related technologies, etc.) and methodologies such as Multi-Criteria Decision Methods (MCDM), Life Cycle Analysis (LCA), Cost-Benefit Analysis (CBA), Carbon Footprint Analysis (CFA), etc.

A variety of sources were used for the development of the different data bases which comprise knowledge extracted from interviews with experts and bibliography within the NOVEDAR Project (which accounts with the cooperation of 11 research groups, 29 relevant water companies and 14 public entities related to the water management, as well as project related engineers, companies and wastewater treatment authorities) Conventional knowledge acquisition methods (scientific and technical literature, conferences, etc.) were also used.

The proposed model for the EDSS is based on a hierarchical decision approach that breaks down a complex design problem (WWTP conceptual design) into a series of issues easier to analyze and to evaluate. The generation of WWTP alternatives is carried out by means of the interaction of different main knowledge bases (KBs). However, the most remarkable is the Specifications Knowledge Bases (S-KB) that collects a complete characterization of the wide range of unit process existing in WWTP. At this moment 274 unit processes are thoroughly characterized by a whole range of parameters encompassed in five main topics: Technical, Influent and effluent characteristics, Costs and  Environmental Impacts.

All treatments proposed by the NOVEDAR_EDSS can be divided into primary and main (secondary or advanced) treatments, according to the level of purification they can achieve.

*Primary treatment.* These treatments are designed to remove coarse solids, grit and therefore the associated fraction in terms of nitrogen, phosphorus and organic matter, but a limited extent. The NOVEDAR_EDSS proposes two options for pre-treatment: a) Coarse and fine screens and Imhoff Tank (functioning as primary treatment); b) Coarse and fine screens, degritting and cylindroconical settler. The guidelines used to select one of these configurations are based on the size of the community and according to bibliographic references and heuristic knowledge (Comas et al., 2004; Ortega de Ferrer et al., 2011).

*Secondary or main treatment.* These treatments are applied to eliminate COD, SS, and depending on the treatment, reduce nitrogen (N) and/or phosphorus (P). More than 40 secondary treatments are included in the NOVEDAR_EDSS. However, taking into account the scope of the study only those more representative for small agglomerations are considered.

### 2.2. COST-BENEFIT ANALYSIS METHODOLOGY

Because the economic assessment through a CBA is one of the novel aspects of the NOVEDAR_EDSS, we will describe the basics of this methodology, including an innovative approach based on the economic valuation of non-market services.

The CBA is made to compare the economic feasibility associated with the implementation of different proposals. CBA main premise considers that projects should only be commissioned when benefits exceed the aggregate costs. Such analysis methodology is based on the net profit calculation for each one of the available options, which is the difference between benefits and costs (Eq. 1).

$$NP = \sum B_i - \sum C_i \qquad (1)$$

where:

*NP* is the net profit; $B_i$ is the value of the benefit item i and $C_i$ is the value of the cost item i.

In the case of investment projects whose life period is more than one year, such as the implementation of a WWTP, the costs and benefits of the project must be adjusted for when in time it occurs. For this reason, the NP must be discounted into present value terms. By means of a properly chosen discount rate, the investor becomes indifferent regarding cash amounts received at different points of time. The net present value (NPV) of an investment is calculated as a function of the NP and the discount rate as shown in Eq. 2.

$$NPV = \sum_{t=0}^{T} \frac{NP}{(1+r)^t} \qquad (2)$$

where:

*NPV* is the net present value; *NP* is the net profit at time t; *r* is the discount rate and, *t* is the time horizon of the project.

The conventional CBA, namely financial analysis, only takes into account costs and benefits with market value. However, taking into account the principles of the WFD, the benefits without market value such as environmental ones also must be considered in the assessment of the economic feasibility of investment projects.

According to Hernández-Sancho et al., (2010), wastewater treatment can be considered a production process in which a desirable output (treated water) is obtained together with pollution (organic matter, phosphorus, nitrogen, etc.) using inputs (costs). Contaminants removed from wastewater are considered undesirable outputs because if they were dumped in an uncontrolled manner they would cause a negative impact on the environment. In this chapter quantification of environmental benefits from wastewater treatment is based on the shadow prices values obtained by Hernández-Sancho et al., (2010) (Table 1). Hence, an indicator of economic feasibility of wastewater treatment technologies considering both internal and external impacts is obtained.

**Table 1**
Shadow prices for pollutants removed from wastewater (€/kg). Note that shadow prices are interpreted positively because they represent the environmental benefits obtained by treating wastewater.
Source: Hernández-Sancho et al., (2010).

| Destination | Shadows prices of undesirable outputs (€/kg) | | | |
|---|---|---|---|---|
| | N | P | SS | COD |
| River | 16.353 | 30.944 | 0.005 | 0.098 |
| Sea | 4.612 | 7.533 | 0.001 | 0.010 |
| Wetlands | 65.209 | 103.424 | 0.010 | 0.122 |
| Reuse | 26.182 | 79.268 | 0.010 | 0.140 |

The integration of this methodology within the NOVEDAR_EDSS is pioneering and enhances the decision-making process due to the integrated assessment of the economic feasibility of a set of technologies under different scenarios and wastewater characteristics considering environmental externalities.

## 2.3. CASE STUDIES

### 2.3.1 Wastewater treatments evaluated

Regarding the primary treatment, previous research established adequate technologies based on the size of community (Comas et al., 2004; Ortega de Ferrer et al., 2011). Moreover, investment costs (IC) and operation and maintenance costs

(O&MC) for such processes are negligible compared with those associated with secondary treatment (Pengfei et al., 2000). In the case of sludge treatment, it is not feasible to consider the design of a complete treatment train since commonly, sludge treatment/disposal in most of the existing facilities of moderate/small size is not carried out at their premises. Although NOVEDAR_EDSS is capable of designing a complete treatment train for a specific wastewater management project, for the purposes of this work only the selection of technologies for secondary treatment were considered in order to carry out a more thoroughly and focused comparison between the selected technologies. Extraordinary conditions, such as flooding of the plant by extremely intense rain or stoppage of units, were also excluded, as these situations were considered exceptional and therefore, did not represent normal operation.

Among the secondary treatment units encompassed in S-KB, the nine more usually applied in WWTPs are presented in this study (Tchobanoglous et al., 2003; Ortega de Ferrer et al., 2011). Table 2 shows a short summary of each technology evaluated regarding its definition, average removal efficiencies of: nitrogen (N); phosphorus (P); organic matter measured as chemical oxygen demand (COD); and suspended solids (SS), IC and O&MC.

**Table 2**.

Secondary treatment technologies under study.

| Secondary Technology | Definition | Contaminants Removal Performance (%) | Associated Costs (€/p.e.) |
|---|---|---|---|
| Ponds System (PS) | Artificial man-made lagoons in which wastewater is treated by natural occurring processes and the influence of solar light, wind, microorganisms and algae. | N: 20-40<br>P: 60-70<br>COD: 60-96<br>SS: 50-90 | IC: $y = 3{,}897.7x^{-0.407}$<br>($R^2 = 0.998$)<br>O&MC: $y = 5.543x + 3{,}127.5$<br>($R^2 = 0.991$) |
| Intermitent Sand Filter (ISF) | Wastewater treated with a well developed aerobic biological community attached to the surface of filter media. | N: 65-95<br>P: 75-99<br>COD: 75-90<br>SS: 85-95 | IC: $y = 2{,}115.5x^{-0.399}$<br>($R^2 = 0.992$)<br>O&MC: $y = 12.026x + 3{,}518.9$<br>($R^2 = 0.992$) |
| Wetlands (CWS) | Pretreatment of wastewater by filtration and settling, followed by bacterial decomposition in a natural-looking lined marsh. | N: 30-70<br>P: 20-60<br>COD: 55-80<br>SS: 60-98 | IC: $y = 947.3x^{-0.188}$<br>($R^2 = 0.991$)<br>O&MC: $y = 14.749x + 3{,}645.1$<br>($R^2 = 0.994$) |
| Trickling Filter (TF) | A fixed bed over which sewage flows downward developing a layer of microbial slime (biofilm), covering the bed of media. | N: 35-50<br>P: 35-55<br>COD: 75-90<br>SS: 50-90 | IC: $y = 12{,}237.0x^{-0.487}$<br>($R^2 = 0.993$)<br>O&MC: $y = 13.504x + 6{,}030.0$<br>($R^2 = 0.998$) |

| | | | |
|---|---|---|---|
| Moving Bed Biofilm Reactor (MBBR) | Based on the aerobic biofilm principle. Carriers made from polyethylene provide large surface and optimal conditions for the bacteria culture to develop. | N: 10-20<br>P: 30-40<br>COD: 20-40<br>SS: 60-80 | IC: $y = 1{,}187.0x^{-0.165}$<br>($R^2 = 0.991$)<br>O&MC: $y = 12.794x + 6{,}031.0$<br>($R^2 = 0.985$) |
| Rotating Biological Contactors (RBC) | Large disc with radial and concentric passages slowly rotating. The alternate exposure to oxygen/sewage promotes the development of a thin layer of biomass. | N: 20-80<br>P: 10-30<br>COD: 70-93<br>SS: 75-98 | IC: $y = 6{,}931.4x^{-0.383}$<br>($R^2 = 0.998$)<br>O&MC: $y = 313.4x^{-0.435}$<br>($R^2 = 0.994$) |
| Membrane Bioreactor (MBR) | Combination of the conventional activated sludge process with a membrane filtration step. | N: 50-90<br>P: 20-70<br>COD: 70-90<br>SS: 85-99 | IC: $y = 5{,}635.3x^{-0.352}$<br>($R^2 = 0.992$)<br>O&MC: $y = 30.150x + 13{,}542.0$<br>($R^2 = 0.985$) |
| Extended Aeration (EA) | Modification of the activated sludge process preferred for small loads, where lower operating efficiency is offset by mechanical simplicity. | N: 50-90<br>P: 15-70<br>COD: 70-90<br>SS: 85-99 | IC: $y = 7{,}946.0x^{-0.460}$<br>($R^2 = 0.997$)<br>O&MC: $y = 30.150x + 13{,}542.0$<br>($R^2 = 0.985$) |
| Sequencing Batch Reactor (SBR) | Fill-and-draw activated sludge system where all the operations (fill, react, settle and draw) are achieved in a single batch reactor. | N: 55-90<br>P: 25-70<br>COD: 70-90<br>SS: 85-99 | IC: $y = 8{,}258.9x^{-0.407}$<br>($R^2 = 0.970$)<br>O&MC: $y = 309.4x^{-0.389}$<br>($R^2 = 0.950$) |

Source: Ortega de Ferrer et al., (2011); Tchobanoglous et al., (2003); Comas et al., (2004).

where:

*x* is p.e.; *y* is total cost expressed as €/p.e. and $R^2$ is the determination coefficient.

2.3.2 Scenarios analysed.

Nine scenarios for small communities are considered in order to highlight the possible differences between treatment technologies. Three different types of wastewater are chosen and three different final destinations were selected for the treated water. The cases are focused in a small community with an estimated population of 1,500 p.e. and an average flow rate of 400 $m^3$/day.

The characteristics of the three standardized types of wastewater (High loaded, Moderate loaded and Low loaded) can be found at Table 3. The selected contaminants concentrations represent the most significant types of wastewater that can be found in WWTPs (Poch Espallargas, 1999). According to Molinos-Senante et al., (2011), after the treatment process, three end-of pipe options have been considered for each of the aforementioned wastewater types: (i) no sale of treated water, (ii) sale of 50% of the treated water and (iii) sale of 100% of the treated water.

**Table 3.** Three main typical compositions of wastewater in WWTPs.

| Parameter | High Loaded | Moderate Loaded | Low Loaded |
|---|---|---|---|
| Population equivalent (p.e) | 1,500 | 1,500 | 1,500 |
| Flow rate ($m^3$/day) | 400 | 400 | 400 |
| Biological Oxygen Demand (mg/l) | 450 | 310 | 110 |
| Chemical Oxygen Demand (mg/l) | 1,250 | 750 | 220 |
| Suspended Solids (mg/l) | 350 | 285 | 100 |
| Phosphorus (mg/l) | 17.0 | 11.5 | 5.0 |
| Total Kjeldahl Nitrogen (mg/l) | 85.0 | 62.5 | 20.0 |
| Nitrate (mg/l) | 4 | 2 | 1 |
| Nitrite (mg/l) | 2 | 1 | 0 |
| Conductivity (µs/cm) | 1,000 | 700 | 400 |

Moreover, according to the prevailing hydrological and ecological circumstances, distribution of sensitive areas varies widely between regions, especially on small populations as they use to be settled in remote areas with higher natural interests (Calleja et al., 2000).This concern particular water bodies which are eutrophic or at risk of becoming eutrophic. In this research, areas with different ecological consideration were considered for the CBA analysis, since the final destination of treated wastewater is crucial for shadow prices calculation.

## 3. RESULTS AND DISCUSSION

### 3.1 Environmental assessment

This section summarises the results relative to the quality of the effluent which have been predicted by using the NOVEDAR_EDSS for the nine scenarios selected (see Section 2.3.2). Subsequently, the suitability of the technologies is evaluated according to the criteria required by UWWTD[4].

According to the EDSS results, almost all main treatments are capable to produce an effluent suitable for discharge in non-sensitive areas (Table 4) with the exception of five technologies which could not overcome the legislation limits in terms of COD concentration treating high-strength wastewater: ISF, CWS, SBR, MBBR and EA. Similarly, TF achieved a bad performance removing SS and PS did not present reliable

[4] Requirements of effluent stated by the Directive 91/271/ECC for small communities:
Non-Sensitive areas: COD:125 mg/l; SS: 35 mg/l.
Sensitive areas: COD:125 mg/l; SS: 35 mg/l; P: 2 mg/l; N: 15 mg/l.

efficiencies relative to both COD and SS. In the case of moderate influent load, only two technologies, TF and PS, do not remove SS at an extent high enough to achieve the quality objectives. In case the load of the influent is low, all the technologies evaluated would be able to obtain an effluent suitable according to the criteria required by UWWTD. Hence, for non-sensitive areas, the technologies of RBC and MBR are the only ones capable to produce an effluent suitable independently of the influent load. In this case, the selection of the most suitable technology should consider other criteria such as the availability of space, environmental impact and economic aspects (Section 3.2). The only technology expected to remove nutrients at concentrations below the limits established for discharge in sensitive area are the MBRs. SBRs also fulfill the requirements regarding nutrients independently of wastewater characteristics. However, if the influent load is high, COD concentration is slightly above the limits and therefore, SBRs might not be a suitable technology in this concrete scenario. In the case of low-charged wastewater and discharge in non sensitive area, all the technologies evaluated are suitable with no exception.

**Table 4.**

Expected concentration of COD, SS, N and P in the effluent. Grey boxes indicates those values non-admissible for an effluent to be discharged in a sensitive areas, and black boxes those values no admissible for discharge in non-sensitive area.

| | COD | | | SS | | | N | | | P | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | High | Moderate | Low | High | Moderate | Low | High | Moderate | Low | High | Moderate | Low |
| PS | 310 | 95 | 53 | 122 | 99 | 35 | 34 | <2 | <2 | 3 | <2 | <2 |
| ISF | 185 | 100 | 31 | 35 | 28 | 10 | 23 | 16 | 5 | 7 | 4 | 2 |
| CWS | 185 | 100 | 31 | 26 | 21 | 7 | 40 | 28 | 8 | 7 | 4 | 2 |
| SBR | 126 | 65 | 21 | 13 | 11 | 2 | <2 | <2 | <2 | <2 | <2 | <2 |
| TF | 96 | 53 | 16 | 100 | 85 | 3 | 40 | 29 | 7 | 7 | 4 | <2 |
| MBBR | 185 | 100 | 31 | 35 | 28 | 10 | 32 | 22 | 6 | 7 | 4 | 2 |
| RBC | 96 | 53 | 16 | 10 | 8 | 3 | 35 | 24 | 7 | 6 | 3 | <2 |
| MBR | 96 | 53 | 16 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 |
| EA | 185 | 53 | 31 | 35 | 8 | 3 | 32 | 21 | 6 | 7 | 3 | <2 |

For a better understanding of the results, Table 5 indicates the technologies that fulfill the requirements stated by the UWWTD both for non-sensitive and sensitive areas in the three scenarios evaluated.

**Table 5.**
Feasible technologies when the effluent is discharged to non-sensitive and sensitive areas for the three considered scenarios.

| **HIGH** | | **MODERATE** | | **LOW** | |
|---|---|---|---|---|---|
| Non-sensitive | Sensitive | Non-sensitive | Sensitive | Non-sensitive | Sensitive |
| RBC | MBR | ISF | SBR | PS | PS |
| MBR | | CWS | MBR | ISF | ISF |
| | | SBR | | CWS | CWS |
| | | MBBR | | SBR | SBR |
| | | RBC | | TF | TF |
| | | MBR | | MBBR | MBBR |
| | | EA | | RBC | RBC |
| | | | | MBR | MBR |
| | | | | EA | EA |

3.2 Economic assessment.

The tool selected to carry out the economic assessment is the CBA. In order to verify the role of the environmental benefits in the feasibility of the wastewater treatment technologies, two different approaches have been developed. Firstly, a conventional CBA have been carried out considering internal costs and benefits whose value is determined by the market. In a second approach the environmental benefits of treating wastewater have been included by considering the shadow price of the pollutants removed during wastewater treatment (Table 1).

The Total Equivalent Cost (TEC) of the selected treatments has been calculated by considering IC and O&MC. In order to express the total cost in "present values", it has been assumed that the expected life of the plant is 30 years (Lundin et al., 2000) and the discount rate is 4%.

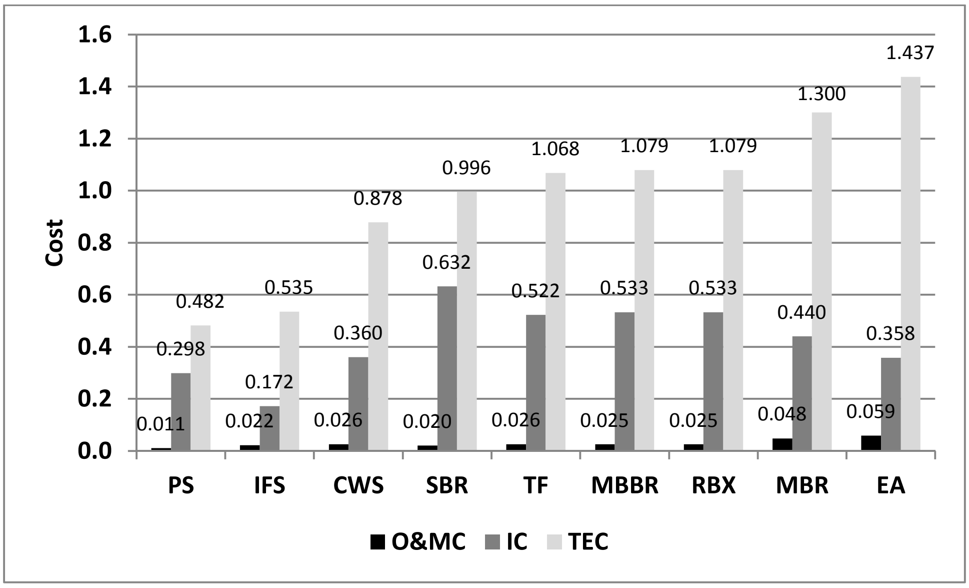


**Figure 1.** Cost comparison for the selected treatments. O&M (M€/year); Investment (M€) and TEC (M€).

Figure 1 shows relevant differences between the 9 evaluated technologies since the maximum TEC, which corresponds to EA, is approximately 3 times higher than the minimum value corresponding to PS. Focusing on O&MC, PS is characterized for its low costs whereas MBR and EA are heading the list of the most expensive technologies. No significant differences are found in terms of O&MC comparing with the other technologies. Regarding IC, the situation is indeed more diverse, being SBRs the most expensive technology and ISF the low cost choice.

During the decision making process, the parameter to take into account should be the TEC since it involves both IC and O&MC during the life-span of the WWTP. In this sense, it is possible to identify three main groups. The first group belongs to those technologies with relative low operation and investment cost like PS, ISF and CWS. Higher costs are found for biofilm technologies as TF, MBBR and RBC. Although SBR is not an attached growth process shares similar economical parameters with this second group. Finally, a third group headed by EA and MBR, at the top of the most expensive technologies. However, it is remarkable that although these last two technologies do not present and excessive investment cost in comparison to SBR or others from the second group, their TEC leads both to the most expensive options due to their higher operation costs.

After costs estimation, the next step to carry out a CBA is to calculate the benefits. In a wastewater treatment project, the only benefits with market value are associated with the sale of reclaimed water. In this sense, and according to the scenarios defined in Section 2.3.2, three options for the reuse of the regenerated water have been evaluated (Figure 2). Based on Spanish Environmental Ministry experiences (MMA, 2007), the value of 0.345 €/$m^3$ as the market price of regenerated water has been allocated.

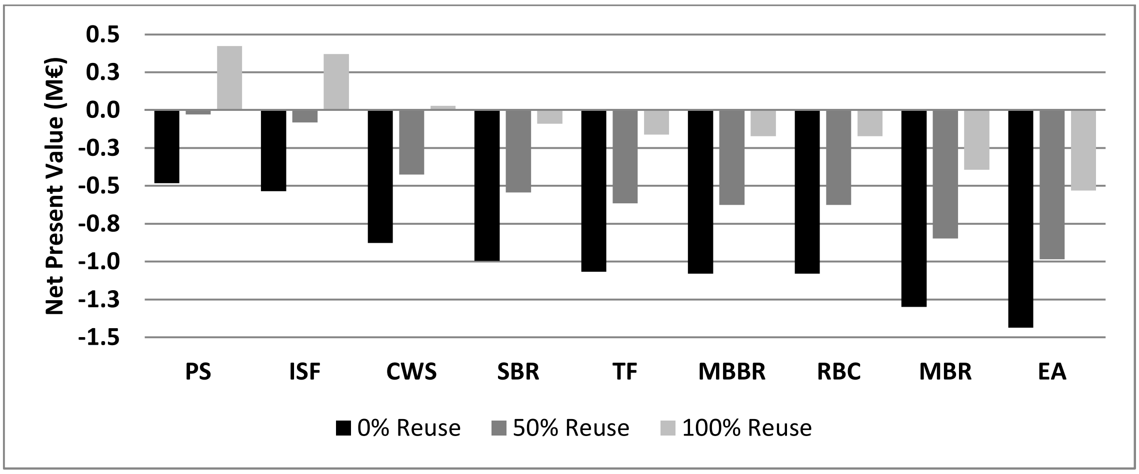


**Figure 2.** Net present value without taking into account environmental benefits for the selected wastewater treatments.

In Figure 2, the net present value calculated for each technology is shown depending on the final destination. Obviously, when there is not sale of reclaimed water, the net profit is negative for all technologies since there is not any income considered. Similarly, when the 50% of the treated water is sold, none of the technologies evaluated are feasible in economic terms since the TEC is again higher than the benefits. Even in the event that all the treated water is sold, only three technologies, PS, ISF and CWS, would obtain benefits after the proposed expected lifespan for the WWTP. The most favored treatments are obviously those entailing not excessive TEC, while MBR and EA, both sharing the highest operation costs, appears as the less indicated options for the economic feasibility of the plant.
In order to improve and complete the economic assessment, a second feasibility study has been carried out. In this case, the CBA includes the monetary value of the environmental benefits derived from wastewater treatment. Hence, the new economic feasibility indicator takes into account internal and external impacts and will depend on the amount of pollutants removed from wastewater. Therefore, the case studies presented distinguish between high, moderate and low load in the influent.

By considering the volume of pollutants removed during the treatment process (kg/year), and their shadow prices (€/kg) depending on the destination of the effluent (Table 1), we can calculate the environmental benefits from wastewater treatment for the nine scenarios evaluated (Table 6). Note that the environmental benefits are calculated by considering the life-span of the WWTPs (30 years) and are expressed in present value. According to the previous environmental assessment, several technologies are capable of producing an effluent suitable to meet the requirements laid down by the legislation. Therefore, in the decision-making process, economics acquires special relevance.

| Technology | High Loaded | | | Moderate Loaded | | | Low Loaded | | |
|---|---|---|---|---|---|---|---|---|---|
| | *100% reuse* | *50% reuse* | *0% reuse* | *100% reuse* | *50% reuse* | *0% reuse* | *100% reuse* | *50% reuse* | *0% reuse* |
| **PS** | 8.95 | 6.94 | 4.94 | 6.57 | 5.11 | 3.64 | 2.30 | 1.77 | 1.24 |
| **ISF** | 6.78 | 5.28 | 3.78 | 5.07 | 3.94 | 2.82 | 1.75 | 1.36 | 0.96 |
| **CWS** | 5.66 | 4.36 | 3.07 | 4.25 | 3.27 | 2.30 | 1.49 | 1.14 | 0.79 |
| **SBR** | 9.83 | 7.59 | 5.35 | 6.93 | 5.36 | 3.80 | 2.37 | 1.81 | 1.25 |
| **TF** | 5.63 | 4.35 | 3.07 | 4.11 | 3.18 | 2.24 | 1.66 | 1.27 | 0.88 |
| **MBBR** | 6.19 | 4.80 | 3.41 | 4.63 | 3.59 | 2.54 | 1.61 | 1.24 | 0.87 |
| **RBC** | 6.30 | 4.86 | 3.41 | 4.68 | 3.61 | 2.54 | 1.66 | 1.27 | 0.88 |
| **MBR** | 9.84 | 7.60 | 5.36 | 6.93 | 5.37 | 3.80 | 2.39 | 1.84 | 1.28 |
| **EA** | 6.19 | 4.80 | 3.41 | 4.79 | 3.71 | 2.63 | 1.66 | 1.28 | 0.90 |

**Table 6.** Estimated environmental benefits (M €) for the selected wastewater treatments depending on the scenario for 30 years.

The greatest environmental benefit is obtained for two specific scenarios: i) reuse of 100% of the regenerated water (since the shadow price of each pollutant is higher for this scenario) and ii) treatment of high loaded wastewater, because in this case eliminations are higher, which contributes to maximize the environmental benefits. Comparing the technologies assessed, MBR and SBR present the highest environmental benefits for the 9 scenarios analyzed, closely followed by PS. On the other hand, the lowest environmental benefit is obtained when the wastewater is treated using CWS and TF technologies.

Figures 3, 4 and 5 show the net present value for the three scenarios studied (high, moderate and low load) considering the three options regarding water reuse. The economic assessment has been carried out only for those technologies that are viable from an environmental standpoint.

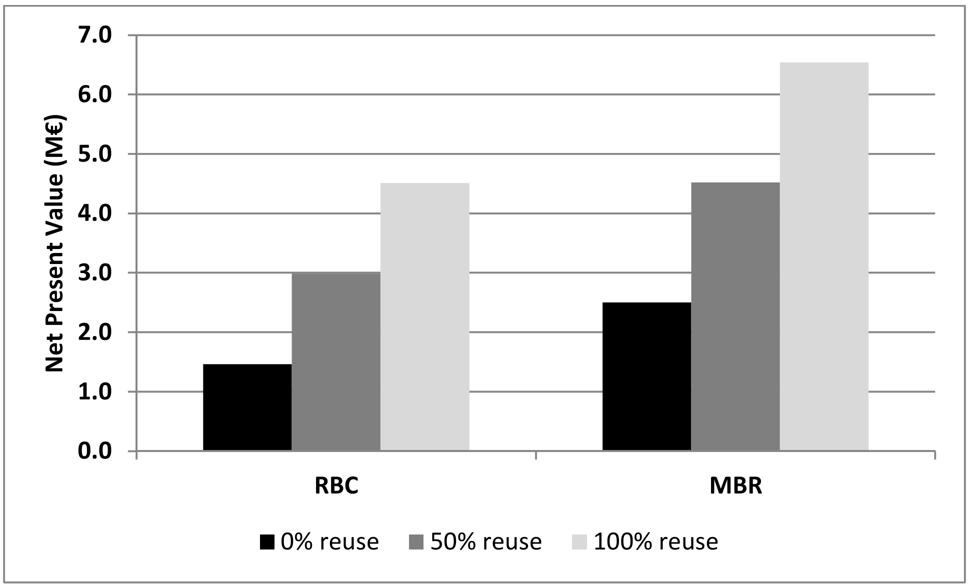


**Figure 3.** Net present value taking into account the environmental benefits for the selected wastewater treatments for the high loaded scenarios.

According to the environmental assessment, treating highly loaded effluents, only RBC and MBR technologies will be feasible if the regenerated water is discharged to non-sensitive areas. On the contrary, when the effluent is discharged into sensitive areas, only MBRs will stand as the only viable technological choice. From an economic point of view, as shown in Figure 3, the most suitable technology is the MBR since it presents the highest net present value regardless the percentage of water reused. Moreover, it is observed that both technologies are feasible even if regenerated water is not reused, due to the addition of environmental benefits criteria in the economic analysis.

Figure 4 shows the economic assessment of feasible technologies from the environmental point of view, when the load of the influent is moderate. It is noted that the net present value of MBR and SBR is clearly higher than the one calculated for other technologies due to their high performance removing pollutants but not for their cost, since for example, MBRs have the second largest TEC from all the technologies assessed (Figure 1). However, when the feasibility study includes externalities, the greatest environmental benefits of these technologies allow offset their higher cost.
It is also interesting to note that despite ISF achieve average environmental benefits (Table 7) compared with other technologies, it is in the top rank (third highest net present value) due to its low TEC.

Remaining technologies (CWS, MBBR, RBC and EA) have very similar net present values being approximately 1.5, 3 and 4.5 M€ for 0%, 50% and 100% reuse respectively. Thus, when the treated water is either discharged into non-sensitive or sensitive areas, SBRs generate the highest net present value over the useful life of the WWTP, achieving the quality requirements stated by the legislation.

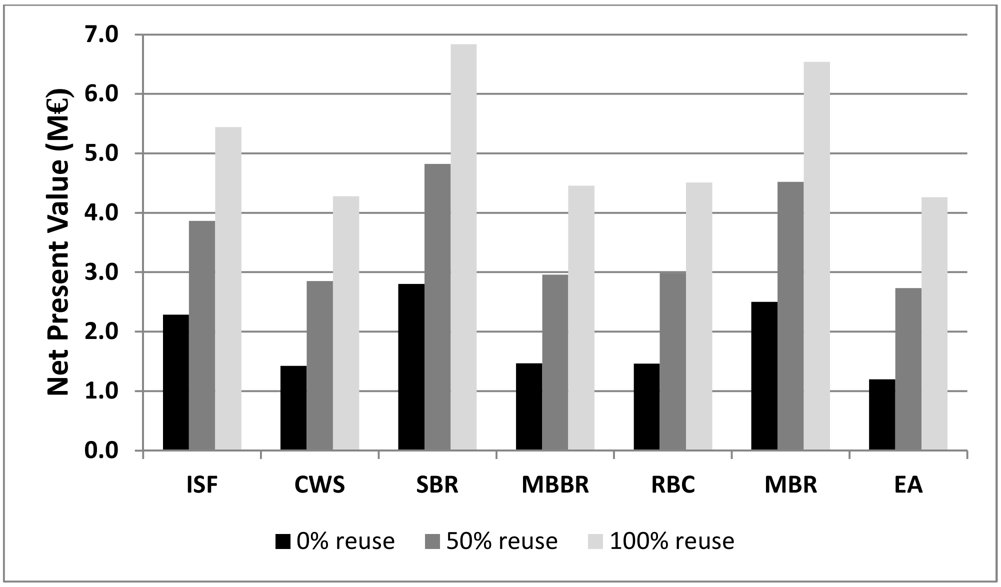


**Figure 4.** Net present value taking into account the environmental benefits for the selected wastewater treatments for the moderate loaded scenarios.

Whether the load of the influent is low, all technologies evaluated are suitable to achieve the quality requirements required by UWWTD. Thus, Figure 5 shows the net present value of the 9 technologies assessed for the three reuse scenarios considered. In this concrete scenario, we found negative net present values for 6 out of 9 technologies (CWS, TF, MBBR, CBR, MBR and EA) which consequently, would not be considered viable from an economic point of view. This situation is observed only in case reclaimed water is not sold, even though externalities are included in the feasibility study. In the other two scenarios (50 and 100% water reuse), the net present value of all technologies is positive, i.e., they are economically viable. The technologies with the lowest TEC (PS and ISF) have the highest net present value. Because the influent load is low, the amount of pollutants removed is small and therefore the environmental benefits do not outweigh the higher costs of other technologies with better performance removing pollution. Hence, if the load of the influent is low, extensive wastewater technologies such as PS, ISF or CWS will be very suitable from both environmental and economic point of view.

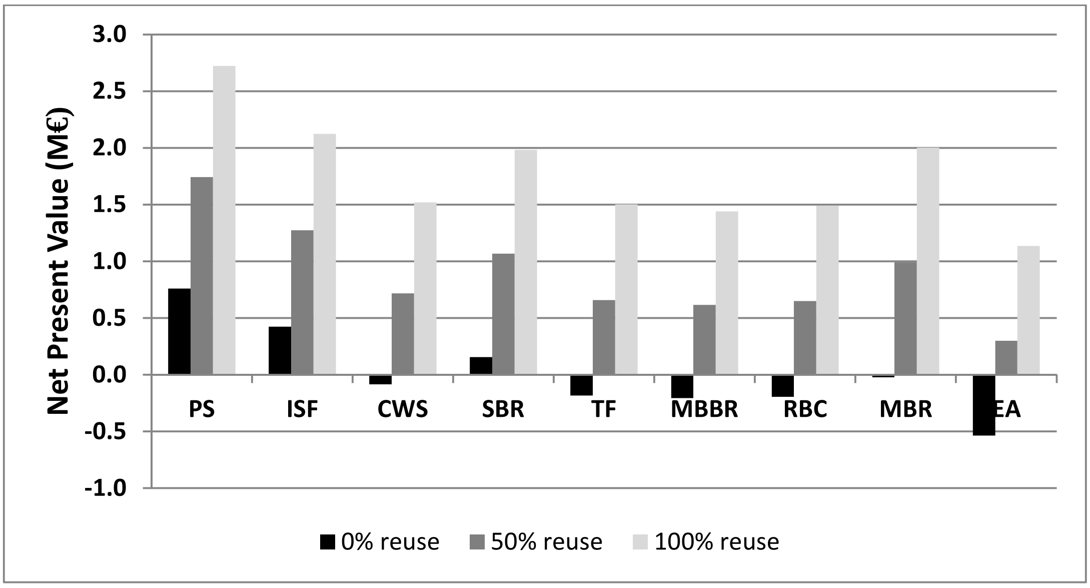


**Figure 5.** Net present value taking into account the environmental benefits for the selected wastewater treatments for the low loaded scenarios.

## 4. CONCLUSIONS

This work presents a complete economic feasibility study of different wastewater treatment technologies not only based on conventional cost-benefit methodologies but also in the economic value of the environmental benefits derived from wastewater treatment. The main highlight is the integration of the aforementioned methodology within an environmental decision support system developed to generate feasible flow-diagrams for specific wastewater management scenarios.

In order to show the usefulness of this approach, ten different technologies set-up for the secondary treatment step in small WWTPs are assessed from an environmental and economic point of view. In general, the technologies evaluated have significant differences in relation to their total equivalent cost being EA the most expensive technology and PS the cheapest one. Afterwards, nine scenarios regarding influent load and water reuse options are evaluated. Differences concerning whether the treated water is discharged to non-sensitive or to sensitive areas are also explored, which constitutes one of the key factors during the decision-making process to select which treatment is most adequate, particularly for medium or high loaded influents.

The environmental assessment has shown that treating low influent loads, all the assessed technologies are suitable, regardless the destination of the effluent. However, if the load is moderate or high, some technologies are not adequate particularly if the treated water is discharged to sensitive areas. MBR technology is the only one with the potential to produce an effluent suitable for all analyzed scenarios.

The conventional CBA without taking into account environmental benefits verifies that PS, ISF and CWS are the only feasible technologies as long as all the treated water is reused. When environmental benefits are included in the analysis, all technologies assessed are feasible for treating high and moderate loads. In this case, MBR (high load) and SBR (moderate load) achieves the best rank.

In contrast, 6 of the 9 technologies evaluated are not economically feasible treating low loaded influents when the effluent is not reused. In this case, extensive wastewater treatment technologies are very suitable from both environmental and economic point of view. In this sense, although EA is an intensive treatment widely used in populations over 1,000 from an economical point of view is one of the less favoured options to implement in small agglomerations.

The implementation of WWTPs in small agglomerations is a challenge that should be addressed in the near future. In this context, the EDSS are tools contributing to improve the sustainability of WWTPs since allow identifying the most suitable technologies of a set of possibilities. Hence, the EDSS presented in this chapter is particularly useful because it integrates environmental and economic aspects. The inclusion of the economic value of the environmental benefits in the feasibility study enable to justify the implementation of technologies aimed to increase the level of environmental protection.

**ACKNOWLEDGMENTS**

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# Chapter 7

## A new tool for the integrated assessment of process flow diagrams devoted to remove nutrients in wastewater treatment

*The aim of this work was to study and explore the NOVEDAR_DSS sensitivity of the implemented integrated assessment capabilities. This chapter presents the results obtained by the EDSS after the implementation and validation of a knowledge based module for the WWTP alternative generation, selection and assessment depending on the initial C/N of different influent. The module is based on a decision tree to build the knowledge base*

# Chapter 7: New Tool for the Integrated Assessment and Selection of Innovative Wastewater Treatment Technologies for Nutrient Removal

## 1. INTRODUCTION

Degradation of water bodies is strongly associated with excess levels of nitrogen and phosphorus, the so-called eutrophication, and constitutes nowadays a relevant environmental issue. Runoff from agricultural activities and discharges of inadequately treated wastewater (WWTP) can cause imbalances in nutrient levels that disrupt local ecosystems, particularly in sensitive areas. Therefore, this issue is being particularly addressed in the legislation of different countries, although with different approaches. On the one hand, European legislation pursues to reach a good ecological status of water bodies by 2015 using the Urban Wastewater Directive (UWD), which defines the required effluent quality criteria following emission-based regulations in terms of COD, BOD and nutrient concentration. The strictest effluent concentrations considered in the UWD are below total nitrogen (TN) levels of 10 mg L-1 and total phosphorus (TP) levels of 1 mg L-1, being such limits based primarily on plant size (> 100,000 population equivalent). On the other hand, in North America permits are determined at the state (or provincial) level based on imission criteria, which considers the requirements of the receiving stream and translates them to locally different effluent requirements. As an example, treatment facilities of specific areas have to meet the perceived limit of treatment effluent standards[1]: 1.5 to 3.0 mg L-1 for TN and 0.07 to 0.1 mg L-1 for TP.
Thus, meeting new and stricter limits usually requires retrofitting of existing facilities or the design and construction of new ones. In this context, inadequate decisions made during the preliminary stages of a wastewater management project usually lead to the construction of plants characterized by high operational and maintenance costs, lack of robustness, and inefficient nutrient removal. In fact, conceptual design should involve a more complex evaluation methodology with respect to multiple criteria at the same time i.e. environmental, economical, technical and legal. This growing complexity requires new tools to manage and process the exhaustive knowledge from conventional and leading-edge technologies, integrating the aforementioned criteria. In this context, a software tool, the decision support systems, bring together all these requirements and support complex decision making processes. When the decisions are based on an environmental domain, this tool is referred as environmental decision support system (EDSS). They apply expert knowledge to arrive at recommendations for various options, improving the consistency and quality of those decisions[2,3,4]. EDSSs integrate on their architecture different fields of expertise[5,6] such as statistical/numerical methods, environmental ontologies, heuristic knowledge, coupled models, databases, multicriteria and assessment tools, with the aim to assist decision makers. Considering wastewater management issues, an EDSS should satisfy a

high number of scenarios, integrating information about leading-edge technologies and considering specific objectives and technical criteria to design and assess efficient WWTP alternatives. This work proposes the use of an EDSS which contemplates the three dimensions of sustainability: environmental, social and economic needs.

-The environmental vector: treatment facilities are not solutions exempt of associated impacts which highlights the importance of this vector. Currently, different methodologies have been developed under the concept of the life-cycle perspective, filling this gap. Its consideration during the early design (or upgrade) of WWTPs is crucial according to the new sustainability paradigm7.

-Economy: plays a central role in any type of WWTP analysis. For example, the UWD considers that the inclusion of more integrative and innovative approaches regarding the economic valuation of WWTP alternatives is of the upmost importance. Although the conventional cost-benefit analysis is still a valid tool8, new approaches also considers the environmental benefits derived from implementing measures or projects, assigning them a monetary value9.

-Technical/operational criteria: the growing number of innovative treatment technologies which can be implemented for the very same case provides water managers with a variety of alternatives to deal with complex types of wastewaters10,11. As the areas designated as sensitive are increasing, the interest shifts to enhanced biological processes designed to achieve nutrient removal, incorporating anaerobic/aerobic/anoxic stages, phosphorus precipitation or tertiary treatments (ozonation, UV disinfection, chlorination, nanofiltration, etc.). In order to adopt suitable treatment schemes, the C/N ratio of the wastewater is a design parameter of the upmost importance to ensure an optimum biological performance12,13. For example, the treatment of low C/N ratio influents might need an additional carbon source (postanoxic denitrification), increasing the operational costs. However, other strategies can be implemented as well, such as the reduction of TN from specific streams (head returns) using the innovative deammonification process.

This paper presents the application of a decision support system, the Novedar_EDSS, developed to assist decision-makers to upgrade or design complete process flow diagrams (PFDs) for different wastewater management scenarios, promoting the implementation of reuse criteria.

## 2. MATERIALS AND METHODS

### 2.1. Knowledge-based methodology (KBM)

The Novedar_EDSS has been conceived as integrated software employing artificial intelligence techniques combined with different analytical tools: Multicriteria Decision Analysis (MCDA) methodologies14,15, Life Cycle Analysis16 (LCA), Cost-Benefit Analysis (CBA) and Environmental-Benefit Analysis17 (EBA). The EDSS core consists of two different knowledge bases: specifications (S-KB) and compatibility (C-KB) built with expertise knowledge regarding WWTP technologies (gathered from Novedar Project partners, scientific literature, project related engineers and interviews with companies and wastewater treatment authorities). S-KB characterizes 280 unit processes by a whole range of parameters encompassed in different topics: Influent quality, effluent characteristics, impacts, costs, etc. C-KB establishes the type of interaction amongst the units composing the overall treatment scheme. A data processing module (DPM) creates a functional network structure where all suitable process flow diagrams for any specific scenario are embedded providing the whole response surface. The architecture of the EDSS is based on a hierarchical decision approach and requires quantitative and qualitative information, heuristics and the use of reasoning processes (expert judgment). Therefore, a complementary rule-based system based in S-KB was installed in order to improve the consistency of the results. Exhaustive information about the EDSS structure, internal knowledge organization, model selection and methodologies implemented has been published elsewhere18,19,17.

**2.2. Multidisciplinary approach: Including the environmental and economic vector**

The application of wider sustainability criteria is essential in order to identify real environmental impacts from treatment processes. The life cycle perspective entails the consideration of direct impacts associated to the discharge of the treated effluent (end-of-pipe approach), combined with indirect impacts associated to the inputs (materials and energy use) and outputs (emissions and waste generated). The most widely accepted and well-established procedure to quantify the environmental impacts associated with a product or process throughout its whole life cycle is the Life Cycle Assessment21,22 (LCA) and its incorporation in any analysis must contribute to improve the decision-making23,24,25. Two highly relevant impact categories in Life-Cycle Assessment for WWTPs, the Eutrophication Potential (EUP) and Global Warming Potential (GWP)26,27 are implemented in the EDSS. Reliability of eco-toxicity related categories (highly influenced by priority pollutants and heavy metals concentration) is still controversial and might not represent satisfactorily wastewater treatment processes28,29,30,31,32,33. Nevertheless, further implementation of new impact categories is feasible in the Novedar EDSS.

Regarding economy aspects, cost–benefit analysis (CBA) is fully valid as an instrument for decision makers34,35,17. Based on conventional CBA, economy experts have made great efforts in order to develop new approaches for economic valuation of WWTPs, able to quantify the avoided damage to the environment through the assignment of a monetary value. Since the estimation of environmental benefits is not determined by the market, these improvements highlight the relevance of wastewater treatment for the environment and society36,37,17. In this sense, the EDSS can conducts both CBA and Environmental Benefit Analysis (EBA) following the empirical approach shown in

Hernández-Sancho38. This work shows its usefulness estimating shadow prices (monetary value for those goods arising from human and productive activities which have no market value and have substantial environmental impacts) of undesirable outputs typical of wastewater treatment processes.

### 2.3. Scenario selection

Since the most remarkable differences between facilities lie in the technologies used for secondary (biological) and tertiary treatments, this paper will particularly address the selection of such technologies. Four scenarios were selected according to population size, influent characteristics and effluent requirements, thus representing typical wastewater compositions (Table 1).

| Input Data | | Scenario A | Scenario B | Scenario C | Scenario D |
|---|---|---|---|---|---|
| Scenario characteristics | Peq | 200,000 | 80,000 | 20,000 | 2,000 |
| | Flow-rate $(m^3 \cdot d^{-1})$ | 45,000 | 22,000 | 5,000 | 600 |
| | Hydraulic Variations | Low | Medium | High | High |
| | Discharge requirements | Sensitive area | Sensitive/reuse | Sensitive area | Sensitive area |
| Influent characteristics | Total Suspended Solids | 80 | 80 | 300 | 300 |
| | COD | 400 | 400 | 800 | 800 |
| | Total Nitrogen | 65 | 45 | 65 | 65 |
| | C/N Ratio | 6 | 9 | 12 | 12 |
| | Total Phosphorus | 13 | 10 | 15 | 15 |

(Peq: population equivalent; COD: Chemical Oxygen Demand; Influent characteristics are expressed in mg•L-1)

**Table 1.** Scenario selection according to different influent characteristics

Data from each scenario constitutes the input information the user introduce to the EDSS. After the data entry stage, the software is able to rank the most feasible secondary treatment units, proposing additional strategies (for example, methanol addition) depending on parameters such as the C/N ratio. It corresponds to the user to select one technology (normally the one that achieved the highest score), and then the EDSS will proceed with the design of the complete process flow diagram (PFD), providing the user with a complete set of estimative output data, which can be used for carrying out comparisons between different feasible designs, in case the user needs to consider various options.

Scenarios A and B correspond to large and medium plants serving a population of 200,000 and 80,000 population equivalent (peq) respectively, whereas C and D tackle with the design of small facilities (20,000 and 2,000 peq respectively), where primary settling is not considered and sludge stabilization is carried out during the biological process. The lack of primary settling increases influent strength (higher solids and COD) of scenarios C and D. Another characteristic factor related to population size is the

hydraulic variations in the influent (daily, weekly, monthly or seasonal), more relevant in small WWTPs treating lower flow-rates, thus requiring specific solutions in some cases.
Concerning the effluent quality, the four scenarios must comply with limits designated in the UWD (although different criteria can be easily implemented in the EDSS) for discharge in sensitive areas: COD: 125 mg•L-1; Total Suspended Solids (TSS): 35-60 mg•L-1; TP: 2 mg•L-1; TN: 15 mg•L-1), for peq <100,000 (scenarios B, C and D), and TP: 1 mg•L-1; TN: 10 mg•L-1 for peq >100,000 (scenario A). In particular, reuse options are promoted for scenario B, where a flow rate of 7,000 m3d-1 (30% of the total sewage load) is assigned for reuse purposes. In this case, it must be considered that effluents designated for reuse must accomplish pathogens elimination at an extent which will be specified in the corresponding legislation. For example, in the case of the United States, any water reuse project that involves discharge to waters must observe with federal and state requirements pursuant to the Clean Water Act. In specific reuse purposes, the removal of nutrients from effluents might not be desired due to its fertilizing potential, which implies saving costs. At this stage, the EDSS considers reuse criteria from the Spanish Royal Decree, although it might be easily adapted to other regulations, according to the user requirements.

Three different C/N ratios (6, 9 and 12) representing typical ranges are studied, considering in all cases the relationship between nitrogen and phosphorus content (higher NT associated with higher TP concentrations). A set of restrictions/case studies were assessed for the four scenarios, according to the three main criteria implemented in the EDSS: economy, environmental impact and operational (Table 2), Therefore, a total number of 9 subcases (combination scenarios-case studies, for example A2, B1, D3, etc.) were assessed. Based on these restrictions (cost optimization, robustness, space constraints, reliability, etc.), the EDSS do not exclude treatment technologies. Instead, restrictions influence the ranking of the proposed solutions following a multicriteria methodology, the weighed sum model39,in which the EDSS calculates a score for each feasible solutions based on the weight or relevance assigned by the user to each desired restriction (for example, 75% cost optimization and 25% reliability). As an exception, two restrictions (plant retrofit and hydraulic variations) are not included in the methodology, since their selection leads to the exclusion of unfeasible alternatives. Therefore, the EDSS will rank only the feasible treatments, and according to the final score. This feature is crucial when three or more different criteria are applied simultaneously. In this study, similar weights have been assigned to each restriction to increase the clarity of the discussion regarding the feasibility of the alternatives proposed by the EDSS. For example, the subcase A3 consists of the selection of units suitable for treating wastewater at low C/N ratio, prioritizing operational criteria (33%), the results from the environmental benefit analysis (33.3%), and the LCA based on the global warming impact category (33.3%).

Table 2. Restrictions considered in the decision-making process for three cases considering the scenarios influent (A, B, C and D).

| Case studies | | 1 | 2 | 3 |
|---|---|---|---|---|
| **Upgrade from Conventional Activated Sludge** | | x | | |
| **Economy** | Cost-benefit analysis | x | x | |
| | Environmental benefit analysis | | | x |
| **Operational criteria** | Operation simplicity | x | xx | |
| | Robustness | x | | |
| | Space constraints | x | | xx |
| | Innovation degree | x | x | xx |
| | Reliability | x | x | |
| **Environmental impact** | Global warming | | x | x |
| | Eutrophication | | x | |

Sub-cases A1, B1, C1 and D1 are slightly different, since they specifically address a current situation in the wastewater management field: the necessity to upgrade existing WWTPs for treating higher flow-rates and implementing enhanced biological treatment to accomplish with new regulations (discharge in sensitive area).
Although the EDSS is able to provide information corresponding to the sludge and primary treatment lines as well, this information is not shown as it is considered far from the current scope.

## 3. RESULTS AND DISCUSSION

### 3.1. Scenario A, B and C: Sensitive area

Table 3 shows the treatments that achieved the highest score for subcases from A1-D1 to A3-D3. After the selection of a specific treatment (recommending the first one in the ranking), the EDSS will provide the user with a set of output data and operational parameters as shown in Table 4

**Table 3**. Technologies selection for the four scenarios and complementary nutrient removal strategies recommended.

| | Case studies | 1 | 2 | 3 |
|---|---|---|---|---|
| Scenario A | | IFAS (UCT) | Bardenpho | BAF |
| | ***Nitrogen strategy*** | Deammonification | MeOH | Deammonification + MeOH |
| | ***Phosphorous strategy*** | P precipitation + tertiary (physicochemical) | P precipitation + tertiary (physicochemical) | P precipitation + tertiary (physicochemical) |
| Scenario B | Sensitive area | IFAS | Johannesburg | BAF |
| | Reuse | MBR (UCT) | Johannesburg + conventional filtration (tertiary) | BAF + membrane filtration (tertiary) |
| | ***Nitrogen strategy*** | not required | not required | not required |
| | ***Phosphorous strategy*** | not required | not required | P precipitation + tertiary (physicochemical) |
| Scenario C | | IFAS (Johannesburg) | SBR | GSBR |
| | ***Nitrogen strategy*** | not required | not required | not required |
| | ***Phosphorous strategy*** | not required | not required | Tertiary (nanofiltration) |
| Scenario D | | Trickling Filter | Hybrid CWs | AnoxAn or IFAS |
| | ***Nitrogen strategy*** | not required | not required | not required |
| | ***Phosphorous strategy*** | P precipitation | P precipitation | not required |

### 3.1.1. Scenario A

Two main restrictions in scenario A increase the complexity for the selection of suitable alternatives. The stricter requirements demanded to large WWTPs of >100,000 peq and the low C/N ratio (6) influence dramatically the selection of technologies, forcing the implementation of additional strategies to ensure the accomplishment of both TN and TP limits.

The first subcase in consideration (A1) corresponds to the upgrade of a conventional activated sludge (CAS) process to achieve nutrient removal. An integrated Fixed-Film Activated Sludge (IFAS) using an UCT configuration was recommended. Given the previous CAS configuration, this upgrade is advantageous since it permits to use the existing secondary settler40. The Hydraulic Retention Time (HRT) of the aeration tank should be increased from 4 up to 9-10 hours (Table 4), which implies no excessive space requirements. To implement the IFAS-UCT configuration, three different compartments are required: the aerobic zone filled with biofilm carrier media (30-40%) for nitrification, an anoxic zone (40%) for denitrification and the anaerobic (15-25%) for TP removal41,42. Regarding the use of additional strategies for nitrogen removal, the EDSS proposes the treatment of head returns using an emergent technology: the deammonification process (partial nitritation+Anammox). This technology is able to efficiently remove 15-20% of the TN load from the influent43. The combination of the enhanced nutrient removal of the UCT configuration with the deammonification of the head returns permits to accomplish with the UWD discharge limits (<10 mg•L-1 TN). From the point of view of the CBA, this option is also favored since, for example, Van Dongen et al.44 estimated operation and maintenance costs for the deammonification process of 0.22 €/Kg N, substantially lower than the price of methanol (0.75 €/Kg N).

A2 restrictions were rather different to those applied in A1. The solution should include technologies reliable, easy to operate and environmentally friendly (from the point of view of LCA). According to the ranking, an activated sludge process designed for nutrient removal was proposed. Although this technology needs large space requirements, this was not a restriction for A2. The Bardenpho configuration was selected due to its capacity to optimize nutrient removal at low C/N ratios45, adding methanol in the second anoxic zone to improve TN removal. The use of methanol is prioritized in this case since it is a more simple and reliable operational strategy. In this case, the aerobic zone is larger compared to A1, due to the lack of carriers. Therefore, 40-50% of the available volume was assigned to the aerobic zone, and then, 20-30% to anoxic and 20% to anaerobic, with a HRT from 18 to 20 (Table 4).

A3 restrictions include space limitations, innovation degree and with less relevance, optimization of environmental benefits and global warming impact category. Selected technology is the Biofilm Aerated Filter (BAF). This option overcomes space limitations and costs in terms of conventional CBA since secondary settlers are not required. Shifting from conventional CBA to the EBA methodology (monetary value of externalities), the economy restriction might not be fully satisfied in this case, since BAF systems are not fully efficient removing nutrients, thus requiring additional strategies. Other advantage is the innovation degree, compared with conventional suspended biomass bioreactors46,47,48. The suggested BAF configuration is a D-N-D compact system of three consecutive tanks of biofilters: predenitrification + nitrification + postdenitrification, being the second anoxic zone the point where methanol is added49,50. The low efficiency of BAF systems leads to high consumption of methanol for predenitrification. In order to reduce this consumption, the implementation of a deammonification process, or even, an acid fermentation of primary sludge, is strongly suggested to ensure effluent TN levels below 10 mg•L-1. Nevertheless, the acid fermentation might have counterproductive effects, and a further detailed analysis might be needed, as the methane production in the anaerobic sludge digester could suffer a theoretical reduction caused by an early degradation of organic matter (acidogenesis) during the fermentation.

Similarly, in spite of the use of processes devoted to phosphorus removal such as UCT or Bardenpho, levels below 1 mg•L-1 cannot be ensured for any of the three subcases. Therefore, TP removal should be complemented by the addition of coagulant salts (ferric chloride -FeCl3- or hydrate aluminium sulphate - Al2(SO4)3-) in the aerobic zone. Considering that phosphorus is also present on solids (0.025 mg P/ mg TSS), TSS concentration at the effluent should be below 20 mg•L-1 to meet the required concentration. Otherwise, a tertiary treatment (membrane filtration) is necessary, although it would involve excessive energy and maintenance costs, particularly in scenario A. As a BAF system is not able to remove phosphorus, TP removal should be carried out with a further tertiary treatment (precipitation), with higher chemical consumption than cases A1 and A2. According to the output data provided by the EDSS (Table 4), the eutrophication potential for all options in scenario A is approximate 40% lower than the average values. The most influencing factors in EUP are those related with the discharge of pollutants into the receiving media. Compared to other scenarios, A has stricter discharge limits for nutrients, which explains the lower EUP impact. On the contrary, global warming potential is generally higher compared to other scenarios due to the high chemicals consumption51, although the energy use is the most influencing factor in the GWP index. Considering a wider picture of the whole plant, GWP values might be partially compensated by the coagulation process (more relevant in A3 as more coagulants salts are required), which improves the retention of nutrients in the sludge avoiding their washout through the effluent. As a result, sludge produced is more adequate for land application due to its high fertilizing properties, representing a positive output in terms of avoided impact. However, these considerations related to the quality of the generated sludge in terms of nutrients are not yet included in the EDSS knowledge-bases.

**3.1.2. Scenario B**

Scenario B characteristics are less demanding for upgrading the configuration of a WWTP, due to the optimum C/N ratio in the influent and a smaller population size (<100,000 peq.) which entails less restrictive nutrient limits. The main characteristic in this case is the reuse demand for 30% of the inflow, which implies specific strategies to satisfy this requirement.

According to the information contained in the EDSS knowledge bases, membrane bioreactors (MBR) are particularly favored to deal with hydraulic variations and simultaneously, to obtain an effluent suitable for reuse purposes52 mainly due to the ultrafiltration process, able to remove bacteria and viruses from treated water. In case B1, taking into account the reuse demand and the hydraulic conditions, the MBR was selected by the EDSS. However, the current version of the software does not allow simultaneous consideration of two streams with different flow rate and purposes (reuse or discharge in sensitive area), which is a shortcoming of the software that will need to be addressed in the near future. Therefore, a different strategy was followed to search for the best option, using the EDSS in two steps. The first consists on introducing as input data the scenario characteristics for treating sewage with a flow rate of 15,000 m3d-1. In that case, an IFAS is suggested as the best option. IFAS systems are effective to buffer hydraulic variations (absorbing from daily to seasonal variations) and adequate for plant upgrades, due to the possibility to take advantage from the existing CAS bioreactor. A configuration including an anaerobic zone could also satisfy the nutrient legislation level for sensitive areas (TP: 2 mg L-1) being the UCT configuration adequate to reach different legislation demands. The second step, devoted to select a technology suitable for the reuse stream, consists on introducing in the EDSS (input data) the influent flow destined to reuse purposes (7,000 m3/day), being the MBR recommended by the EDSS due to the aforementioned reasons. The selection of both treatments is particularly encouraged since subcase B1 is particularly focused on operational criteria, and both systems satisfy most of the restrictions (space constraints, robustness, reliability and innovation degree) being the combination IFAS+MBR feasible for application in real WWTPs at similar conditions40.

In B2, an activated sludge (Johannesburg configuration) was recommended for the design of a new facility, treating all the received influent in the same reactor and following a different strategy to accomplish with reuse criteria. Therefore, after the biological treatment, the main stream of treated effluent can be directly discharged, whereas the reuse stream requires the reduction of the concentration of pathogens. Regarding the considered restrictions, the operation simplicity is the strongest requirement, although conventional CBA, innovation degree and LCA are also considered. Tertiary treatments based on membrane filtration achieved lower scores, due to its high energy and chemicals (backwash) demands. Instead, a conventional coagulation-flocculation process followed by sand filtration, followed by disinfection is more suitable to simultaneously comply with most of the requirements. Various options are included in the EDSS for disinfection (UV, chlorination and AOP processes such as fenton/photofenton). In subcase B2, UV treatment was the proposed option.

Similarly, the recommended option for B3 consists in the treatment of the entire influent stream in a BAF bioreactor followed by tertiary treatment of the reuse stream. The tertiary treatment suggested for this case, particularly triggered by the innovation degree and the environmental benefit analysis, is a nanofiltration process, due to the high quality of the generated permeate. In general, there was no need to implement additional strategies to accomplish with TN removal in B1, B2 and B3, due to the optimum C/N ratio. For example, the BAF configuration proposed in B3 consists in a denitrification-nitrification (D-N), similar to the one proposed for A3, although in this case methanol addition was necessary to equilibrate ratio. Regarding TP removal in B3, the addition of coagulant salts in the primary settlers was recommended, since both streams (direct discharge and reuse) must accomplish with the strict effluent requirements for medium WWTPs (TP: 2 mg•L-1) and BAF bioreactors might not achieve this quality level. As shown in Table 3, subcases B1 and B2 should produce the demanded effluent levels. However, episodes of process instability or sporadic peaks of phosphorus concentration in wastewater are not considered by the EDSS. In these cases, the P precipitation strategy should also be implemented as a prevention strategy in order to overcome such situations.

Due to less restrictive nutrient limits for scenario B, higher impact values in the EUP category were obtained, whereas the quantified values for the GWP were not significantly lower in spite of the decreased use of chemicals. Nevertheless, the population size reduction from scenario A to B promotes the power-demanding membrane technologies as feasible options for treating the stream for reuse. However, even if MBRs are considered the most energy-demanding technology (1.05kWh m-3), the GWP impact values for the BAF in B3 are even higher due to complementary requirements such as the chemical consumption related to the P removal and the energy demands of the nanofiltration step proposed for the reuse stream.

### 3.1.3. Scenario C

IFAS, as seen from previous cases requiring upgrades, was again the proposed technology for C1, implementing a Johannesburg configuration. Indeed it is an attractive solution as long as the investment costs, its main drawback45 are not a restriction. The Johannesburg configuration for C1 would consist in a 20-30% aerobic zone + biofilm carrier media, 50% anoxic and 20-30% anaerobic.

In subcase C2, SBR achieved the most favorable score, using a modified SBR configuration (anaerobic–anoxic–aerobic phases with multiple feeding events over one cycle), which has shown high effectiveness for an efficient N and P removal53. SBRs are characterized by their low space requirements (65-75% less space compared to CAS)54,55, although this situation was not considered in C2. Nevertheless, they are a cost-effective solution since a secondary settler is not required. These characteristics contribute to increase the score of the SBR in the final selection.

Interestingly, C3 selection is again a SBR, using an innovative configuration based on the use of granular biomass, which is in good accordance with the user requirements. Aerobic granular processes operated as sequenced batch reactors (GSBR) are considered suitable alternatives for medium-small WWTPs with high hydraulic variations, and their space requirements are even lower than a conventional SBR56. Economy criteria are also favorable to GSBRs since their operation costs are reduced an approximate 20% due to their lower energy consumption, mainly based on their lower oxygen demand57,58. In this respect, the lowest GWP value registered for all scenarios correspond to this option. The proposed options in C1, C2 and C3 do not need complementary treatments or strategies, achieving effluent concentrations in good agreement with legislation demands. In a similar manner to subcases B1 and B2, the optional implementation of additional phosphorus precipitation might be suggested to confront instability episodes or unpredictable peak concentrations.

**Table 4.** Secondary treatment selection, score, EDSS outputs and operational parameters for cases A, B and C.

| Selected treatment | | HRT | SRT | Cost (M€) | Sludge (Kg $d^{-1}$) | Space ($m^2$) | EUP (gr $PO_4$ eq./$m^3$) | GWP (gr $CO_2$ eq./$m^3$) | Score |
|---|---|---|---|---|---|---|---|---|---|
| **A1** | IFAS (UCT) + Deamon. + P precipitation | 9-10 | 15±2 | 78.3 | 17780.5 | 118,819 | 4.8 | 283.4 | 8.2 |
| **A2** | Bardenpho + MeoH + P precipitation | 18-20 | 20±2 | 55.2 | 20800 | 137,226 | 3.1 | 224.2 | 7.6 |
| **A3** | BAF+Deamon. + MeOH + P precipitation | 6-9 | - | 82.4 | - | 104,540 | 5.4 | 251.8 | 8.7 |
| **B1s*** | IFAS | 9-10 | 15±2 | 11.7 | 4200 | 39,580 | 11.8 | 215.9 | 8.8 |
| **B1r**** | MBR (UCT) | 6-10 | extended | 19.2 | 1280.5 | 26,290 | 10.2 | 230.2 | |
| **B2** | Johannesburg | 15-20 | 20±2 | 23.8 | 7780.5 | 75,370 | 12.2 | 173.8 | 9.2 |
| **B3** | BAF+ P precipitation (membrane filtration) | 6-9 | - | 25.3 | - | 57,460 | 11.9 | 260 | 8.1 |
| **C1** | IFAS (Johannesburg) | 8-15 | 15±2 | 4.8 | 1740 | 23,210 | 9.1 | 170.5 | 8.5 |
| **C2** | SBR (nutrient removal) | 15-25 | 15±4 | 5.3 | 1841.5 | 16,530 | 11.1 | 188.1 | 7.4 |
| **C3** | GSBR | 6-10 | 30-40 | 3.3 | - | 12,870 | 9.8 | 138.3 | 9.3 |
| **D1** | Trickling Filter + P precipitation | 10-15 | - | 1.6 | 54 | 5,694 | 11.8 | 89.4 | 8.3 |
| **D2** | Hybrid CWs | 150±50 | - | 1.3 | - | 14,500 | 10.9 | 71.5 | 7.7 |
| **D3a***** | AnoxAn | 10-20 | - | 1.7 | 156 | 4,500 | 9.5 | 95.4 | 8.2 |
| **D3b** | IFAS | 8-10 | 15±5 | 1.9 | - | 6,830 | 11.3 | 122.3 | 6.8 |

** B1s corresponds to the flowrate designated to sensitive area (15,000 m3 d-1); ** B2r corresponds to the flowrate for reuse purposes (7,000 m3 d-1); *** D3a and D3b are alternative solutions

### 3.1.4. Scenario D: Wastewater treatment in a small facility

Design criteria for WWTP serving medium and large cities do not give satisfactory results in the case of small agglomerations, due to unaffordable operation and maintenance costs in many cases. Facilities devoted to treat sewage for populations below 2,000 peq should rely on consolidated or innovative technologies that allow flexible operation, reliability and low O&M costs, achieving sufficient effluent quality59. In this sense, the use of the Novedar EDSS is of particular interest for decision-makers, since this issue has been specifically addressed during the elaboration of the knowledge bases and the rule-based system60,61. Technologies proposed for this scenario were not based in typical enhanced biological nutrient removal configurations (Table 3). Regarding the C/N ratio, this scenario should not constitute a major challenge in order to comply with discharge limits in sensitive areas, due to the low nitrogen concentration in sewage.

For scenario D1, the suggested option is a trickling filter. Technically, this technology is reliable, presents an excellent balance of space requirements and is easy to operate62. Considering the economy, the cost-benefit analysis is favored due to low power consumption (do not require large power-demanding aeration blowers as suspended growth systems). These features score trickling filters as a feasible option to upgrade existing small wastewater treatment plants (sWWTP). However, the major drawback of tricking filters lies on their low capacity to remove nutrients, although phosphorus removal might be improved implementing a precipitation step. Nevertheless, this technology might be optimum or not in different sWWTP scenarios, depending on wastewater composition.

For case D2, a hybrid constructed wetland (CWs) system was suggested as a suitable solution since no space limitations were set in this case. The design of a hybrid CW for this scenario consists of two stages: parallel vertical flow (VF) beds followed by subsurface horizontal flow wetlands (HF) coupled in series62,63. VF provides nitrification, while denitrification is accomplished simultaneously with COD and TSS removal in the HF64. Besides, CWs have low operation and maintenance costs as HF mostly do not use electric power (the flow is supported only by gravity) and the pumping works in VF are low energy-demanding. To maximize TN removal, the nitrified effluent from VF bed can be recycled to a secondary settling tank. Removal of TP is normally low, although further strategies can be implemented, such as the addition of filter media with high sorption capacity65 or an additional P precipitation step.

An innovative technology, which can be considered in an embryonic development stage, was suggested for D3: the AnoxAn bioreactor (Spanish patent number ES 2 338 979 B2). It combines treatment at different redox conditions and clarification within the same unit, being adequate to produce effluents suitable for discharge in sensitive areas with no additional carbon source or phosphorus precipitation. This option also suits with the demanded space constraints as combines in a single tank the anaerobic and anoxic zone. However, a major drawback for the selection of this technology AnoxAn is the lack of full-scale implementation. In this respect, although the EDSS knowledge bases contains exhaustive information regarding emergent technologies, only those implemented successfully in some real cases were considered for this study. Therefore, the second most scored option, an IFAS, must be highlighted since it fulfills reasonably well two criteria: high innovation degree parameter and low space requirements. As illustrated in subcases A1, B1 and C1, the flexibility of the system enables its implementation in sWWTPs, where hydraulic variations in the influent load are more frequent.

The LCA analysis carried out for the three subcases achieved similar results in terms of impact categories (low energy requirements and lower contaminants depletion) for the different treatments considered. Therefore, the selection of any of the options cannot be supported only considering criteria based on environmental impacts.

**4. CONCLUSIONS**

The design of wastewater treatment plants is a complex exercise that must consider a wide range of objectives in order to select feasible combinations of treatment units able to achieve a specific effluent quality.

This paper presents the recommendations and feasible solutions obtained using an environmental decision support system developed to confront the wide range of typical scenarios that can be found in WWTPs. More concretely, four scenarios were assessed applying different restrictions or user requirements. The application of a decision support system in this context constitutes a further step in the integration of the many aspects related to wastewater management, focused in the new challenges of the XXI century such as the enlargement and upgrade of existing plants, reuse demands, the increasing number of sensitive areas and the selection of biological processes satisfying simultaneously different objectives. The incorporation of multi-criteria decision methods in the evaluation of treatment units enabled to embrace an integrated and comprehensive analysis of several parameters and indicators (e.g., environmental, economic and technical). Based on the combination of these criteria, the EDSS was able to propose different alternatives providing the user with the best option for each case.

For example, the IFAS bioreactor was the most suggested option for the retrofitting of existing facilities. When stricter discharge limits were considered for nutrients, enhanced biological removal technologies (Bardenpho, Johannesburg, etc.) were usually proposed as the preferential choice. Other innovative approaches were also suggested in specific cases (MBR, granular SBR) characterized, among other restrictions, by low space availability. In parallel with the selection of the main treatment unit, specific operational strategies to comply with legal requirements were also assessed (methanol addition, phosphorus precipitation, tertiary treatments, etc.). Such strategies were of particular relevance when the C/N ratio of the influent was not optimum. The EDSS recommendations for substantially different scenarios constitute a highlight for decision makers, since it embraces a variety of different criteria, offering several technological alternatives adapted for each specific situation. Therefore, the proposed approach efficiently explores different possibilities, which should contribute to the development of more efficient and environmentally friendly WWTPs.

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# Chapter 8

## Conclusions

*In this chapter the main conclusions of the thesis are described*

**PhD THESIS**

# 8. Conclusions

This thesis has been developed within the NOVEDAR_Consolider project framework and aims to build an EDSS to support the decision-making during the conceptual design of WWTPs. The most relevant conclusions arising from the research work involved in the development of the NOVEDAR_DSS are listed below.

1. The complexity of the selection process to obtain suitable process flow diagrams is related to the need to integrate both quantitative and qualitative knowledge, at the same time that scientific information and expert knowledge are also required.

2. Has been stated the existence of a wide range of elements (environmental impacts, economic indicators, etc.) that can support the selection of the most appropriate process flow diagrams. Nevertheless, there was no yet a single tool or system able to support such selection in a friendly and easy manner.

3. The need for tools to deal with this complexity in an efficient manner has been satisfied. Different types of knowledge have been properly incorporated using one single tool.

4. The hierarchical decomposition can handle the complexity associated to our wastewater treatment problem. The problem decomposition enables the consideration of the knowledge acquired in the different knowledge bases and allows that these KBs can interact with each other establishing the solid basis to tackle the problem.

5. The NOVEDAR_EDSS constitutes a highlight for decision makers offering technological alternatives adapted for each specific situation or scenario.

6. The EDSS have been revealed as an efficient tool when handling all the elements and problems that have to be faced in our design problem.

7. The system allows the collection and proper management of different sources of knowledge, at the same time that the required results to support the problem are

obtained. Nevertheless, the quality of those results provided by the EDSS will always depend on the quality of the initial information.

**8.** The system offers the chance to explore and consider a wide range of technologies. However, the quality of the current information is dependent of an update procedure, and in order to maintain the current optimum performance and to maximize the EDSS potential in the future the implementation of a regular update protocol is recommended.

With respect to the main conclusions revealed in the results block of the NOVEDAR_EDSS:

- The EDSS constitutes a pioneer approach for implementing and efficient and effective tool to detect potential environmental impacts, also contributing to the decision-making processes of suitable alternatives which incorporate the environmental vector according to the sustainability paradigm.

- The EDSS enable the inclusion of the economic value in the environmental benefits in feasibility studies and allow justify the implementation of technologies aimed to increase the level of environmental protection.

- The incorporation of multi-criteria decision methods in the evaluation of treatment units enabled to embrace and integrated and comprehensive analysis of several parameters and indicators (e.g., environmental, economic and technical). Therefore, the proposed approach efficiently explores different alternatives, which should contribute to the development of more and efficient and environmental friendly WWTPs

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## PUBLICATIONS

M. Molinos-Senante, F. Hernández-Sancho, R.Sala-Garrido and **M. Garrido-Baserba** (2010). *Feasibility Study for Phosphorus Recovery Processes: an Economic Approach.* AMBIO 40 (4), 408-416.

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M. Molinos-Senante, R. Reif, **M. Garrido-Baserba**, F. Hernandez-Sancho, F. Omil, M. Poch, R. Sala-Garrido (2013). *Economic valuation of environmental benefits of removing pharmaceutical and personal care products from WWTP effluents by ozonation*. Submitted to Science of Total Environment.

## CONGRESS CONTRIBUTIONS

**Authors:** M. Garrido, D. Karakashev, I. Angelidaki.
**Title:** Microbial community changes in response of continuous and pulse oleate addition in anaerobic digestion process
**Participation:** Poster
**Congress:** ASPD 5 (Microbial population dynamics in biological wastewater treatment)
**Place:** Aalborg, Denmark **Date:** 24-27.05.2009

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**Authors:** M.Garrido, X. Flores, M. Poch
**Title:** Small Wastewater System selection using knowledge-based methods and multi-criteria evaluation
**Participation:** Poster
**Congress:** IWA conference on Sustainable Solutions for Small Water and Wastewater Treatment Systems (S2Small2010)
**Place:** Girona, Spain **Date:** 19-22.04.2010

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**Authors:** M.Garrido, X. Flores, M. Poch
**Title:** A Decision Support System to Face New Challenges in the Selection of WWTP Alternatives
**Participation:** Oral Presentation
**Congress:** IWA Specialist Conference "Water and Wastewater Treatment Plants in Towns and Communities of the XXI Century: Technologies, Design and Operation"
**Place:** Moscow, Russia **Date:** 2-4.06.2010

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**Authors:** M.Garrido, X. Flores-Alsina, I. Rodriguez-Roda, M. Poch
**Title:** Wastewater Treatment Alternative Selection Using knowledge-based Methods and Multi-criteria Evaluation
**Participation:** Oral Presentation
**Congress:** Spain National Young Water Professional Conference 2010 (SNYWP 2010)
**Place:** Barcelona, Spain **Date:** 16-18.06.2010

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**Authors:**M.Garrido, I. Rodríguez-Roda, X. Flores, M. Poch
**Title:** Development of a DSS for the generation of WWTP configurations alternatives
**Participation:** Oral Presentation
**Congress:** International Congress of Environmental Modeling and Software (EMSS2010) - Intelligent Environmental Decision Support Systems
**Place:** Ottawa, Canadá **Date:** 5-8.07.2010

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**Authors:** M.Garrido, I. Rodríguez-Roda, M. Poch

**Title:** Development of the NOVEDAR_ DSS for the selection and integrated assessment of WWTPs alternatives.
**Participation:** Oral Presentation
**Congress:** Water &Industry 2011. IWA specialist International Conference. NOVEDAR workshop.
**Place:** Valladolid, Spain **Date:** 2-4.05.2011

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**Authors:** M.Garrido, R. Reif, M. Poch
**Title:** Development of a DSS for the generation of WWTP configurations alternatives
**Participation:** Oral Presentation
**Congress:** WATERMATEX. 8th IWA Symposium on Systems Analysis and Integrated Assessment.
**Place:** San Sebastián, Spain **Date:** 20-22.06.2011

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**Authors:** M.Garrido, A. Hospido, R. Reif, M. T. Moreira, G. Feijoo, M. Poch
**Title:** An innovative tool for wastewater treatment alternatives selection integrating knowledge-based methodologies and life cycle assessment.
**Participation:** Poster
**Congress:** IWA 9th Leading-Edge Conference on Water and Wastewater Technologies (LET2012).
**Place:** Brisbane, Australia **Date:** 04-07.06.2012

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**Authors:** M. Molinos-Senante, M.Garrido, R. Reif, F. Hernandez, M. Poch
**Title:** Decision Support System to Select WWTPs Technologies for Small Populations: Environmental and Economic Assessment
**Participation:** Oral Presentation
**Congress:** EcoSTP. Specialised IWA Conference on Ecotechnologies for Wastewater Treatment. Technical, Environmental and Economic Challenges (EcoSTP).
**Place:** Santiago de Compostela, Spain **Date:** 25-27.06.2012

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**Authors:** R. Reif, M.Garrido, M. Poch
**Title:** IEDSS as a Tool for the Integrated Assessment of Conventional and Innovative Wastewater Treatment Technologies for Nutrient Removal.
**Participation:** Oral Presentation
**Congress:** International Congress of Environmental Modeling and Software (EMSS2010) - Intelligent Environmental Decision Support Systems
**Place:** Leipzig, Germany **Date:** 02-05.07.2012

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**Authors:** M.Garrido, J.Comas, M. Poch
**Title:** Multi-criteria decision support system for WWTP.
**Participation:** Oral Presentation
**Congress:** AtWAT. Specialised Workshop in Advanced Tools for Wastewater Treatment
**Place:** Tiruchirappalli, India **Date:** 28-29.01.2013

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## LECTURER RESUM

- Lecturer at **Ecotech SUDOE Master Course "Tools for the sustainable management of wastewater"**. University of Girona, 5-8 November, 2012.
- Lecturer at **XII International Summer School on the Environment (ISSE 2012): LCA and water management related issues**. University of Girona, 3-7 September, 2012.

- Event coordinator and lecturer at **4th NOVEDAR Summer School in Environmental Decision Support Systems (EDSS): A Tool for the Wastewater Management in the XXI Century.** Catalan Institute for Water Research, 4-8 July, 2011.

**CONFERENCE AND SEMINARY ATTENDANCE AS PHD STUDENT**

- **Seminars:** *Ecoeficiency en WWTPs: Challenges of the XXI century***.** IV Anual Project Conference of the Novedar_Consolider. Barcelona, December 15th, 2010; *Economic efficiency challenges at WWTPs***.** III Anual Project Conference of the Novedar_Consolider. Valencia, December 14th, 2009.
- **Conferences:** *IV Jornades Tècniques de Gestió de Sistemes de Sanejament d'Aigües Residuals.* ENERGIA I SANEJAMENT. Barcelona, April 1st 2009; INNOVA-MED CONFERENCE. Innovative processes and practices for wastewater treatment and re-use in the Mediterranean region. October 8-9, 2009. Girona, Spain**;**
- **Courses:** 2nd NOVEDAR Summer School. *Advanced Treatment and Management of Sewage Sludge* offered by the University of Barcelona, and organized by the NOVEDAR Consolider. Barcelona, July 6-10, 2009; Summer school about *Model-Based Design, Operation and Control Wastewater treatment plants* offered by Centro de Estudios e Investigaciones Tecnológicas (CEIT). San Sebastian, July 13-17, 2009; NOVEDAR course. *WWTP sludge valorization: From theory to industrial experiences*. Offered by the University of Cádiz, and organized by the NOVEDAR_Consolider. Cádiz, February 15-17, 2010.
- **Meetings:** Assistance to the NOVEDAR Meeting for PhDs and post-doctoral researchers. Santiago de Compostela on May 7th-9th, 2009 in the School of Engineering; NOVEDAR_Consolider **Working meetings** attendance: Barcelona; June 4th, 2009; Santander; June 15th -16th, 2009; Valladolid; June 17th -18th, 2009; Cadiz; February 18th-19th , 2010; Girona, May 10th -13th, 2010; Santiago de Compostela; December 13-17th, 2010; November 7-8th ; Valencia, February-March, 27th -3rd, 2011.

**OTHER DATA:**

**Secretary** and **Co -founder** of the university association I.A.E.S.T.E (The International Association for the Exchange of Students for Technical Experience) from 2004 to 2006 at Girona University. Polytechnic Faculty at UdG.

**Event coordinator** of the 2nd NOVEDAR_Consolider **Meeting for PhDs and post-doctoral researchers** at Girona (Spain).

**Event organizer** of the NOVEDAR SUMMERSCHOOL about decisions support systems held in the Catalan Institute for Water Research (ICRA).

**Reviewer** of several **IWA conferences** (II Spain National Young Water Professionals Conference, Water Reuse 2011 Conference, etc.)

**Driving License B1** and car availability.

**Advanced Scuba Diving License** (**PADI)** and experience.