A knowledge management methodology for the integrated assessment of WWTP configurations during conceptual design

M. Garrido-Baserba, R. Reif, I. Rodriguez-Roda and M. Poch

ABSTRACT

The current complexity involved in wastewater management projects is arising as the XXI century sets new challenges leading towards a more integrated plant design. In this context, the growing number of innovative technologies, stricter legislation and the development of new methodological approaches make it difficult to design appropriate flow schemes for new wastewater projects. Thus, new tools are needed for the wastewater treatment plant (WWTP) conceptual design using integrated assessment methods in order to include different types of objectives at the same time i.e. environmental, economical, technical, and legal. Previous experiences used the decision support system (DSS) methodology to handle the specific issues related to wastewater management, for example, the design of treatment facilities for small communities. However, tools developed for addressing the whole treatment process independently of the plant size, capable of integrating knowledge from many different areas, including both conventional and innovative technologies are not available. Therefore, the aim of this paper is to present and describe an innovative knowledge-based methodology that handles the conceptual design of WWTP process flow-diagrams (PFDs), satisfying a vast number of different criteria. This global approach is based on a hierarchy of decisions that uses the information contained in knowledge bases (KBs) with the aim of automating the generation of suitable WWTP configurations for a specific scenario. Expert interviews, legislation, specialized literature and engineering experience have been integrated within the different KBs, which indeed constitute one of the main highlights of this work. Therefore, the methodology is presented as a valuable tool which provides customized PFD for each specific case, taking into account process unit interactions and the user specified requirements and objectives.

Key words | conceptual design, integrated assessment, knowledge bases (KBs), process flow diagram (PFD), wastewater treatment plants (WWTP)

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INTRODUCTION

The wastewater life cycle 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 facilities. When considering the sequence of decisions made during a typical wastewater management project it is important to note the different impact of those decisions as the project proceeds. Opportunities to reduce costs and enhance the wastewater treatment plant (WWTP) value decline as the project proceeds (Daigger 2011). Thus, taking into account the remarkable importance of the decision making during the earlier conceptual design of WWTP, an innovative methodology framed at that stage has been developed.

The range of design options under consideration is higher during the initial stages of WWTP projects: type and degree of treatment, local conditions of treatment plants, emergent technologies to apply, specific objectives, etc. Thus, considering that recent years have seen the arising of new technologies capable of treating wastewater to an appropriate quality degree, it is important to rely on tools that facilitate the selection of the most suitable solutions from this wide range of options. Traditional design rules

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used by engineers are frequently too limited in the case of modern configurations. Satisfying a variety of objectives (such as effluent requirements, investment costs, environmental issues, operational costs, etc.) and taking into account multiple criteria (e.g. Life Cycle Analysis (LCA), environmental benefits, etc.) also increases the complexity of the challenge, such that selection of the most appropriate plant design becomes a very difficult task, even for experienced designers (Rivas *et al.* 2008).

Although there are many process-specific technologies capable of adequately treating wastewater, no single technology or group of technologies has been developed to provide a global solution for the almost infinite number of wastewater scenarios. Available technologies are combined and adapted in a treatment train to meet specific requirements, and this train is represented by a process flow diagram (PFD). The number of processes in a treatment train has been steadily growing, thus increasing the difficulty of selecting an optimum sequence (Joksimovic *et al.* 2006; Hamouda *et al.* 2009). Compiling all the possible wastewater treatment trains, Chen & Beck (1997) noted that as many as 50,000 alternatives need to be considered as possible PFDs to achieve sustainable wastewater treatment, and Joksimovic *et al.* (2008) indicated that considering only 44 treatment unit processes, the total possible combinations of these units was 1.76×10^{13}. This means that during the conceptual design process at least the same number of decisions should be taken. Given this context, powerful decision-making tools are needed to facilitate the design, and simultaneously, to satisfy multiple-objective, and multiple-user requirements (Rodríguez-Roda *et al.* 2000; Poch *et al.* 2004; Alemany *et al.* 2005; Matthies *et al.* 2007; Flores-Alsina *et al.* 2008; Aulinas *et al.* 2011). The current incapacity to explore the whole response surface of potential solutions has led to the development of new knowledge methodologies to manage such an amount of information.

To address the problems of WWTP design, a novel knowledge-based methodology capable of generating all viable PFDs and supporting the selection of the most suitable option for any specific scenario is proposed. Thus, in this paper we present a methodology addressed to tackling two of the main challenges in the current complexity in the design of WWTP: (1) the appropriate assessment of the most suitable PFD alternatives, evaluating, at conceptual level, the performance, operation and efficiencies of those different options; and (2) the integrated assessment, providing information for each PFD about LCA, Cost-Benefit Analysis (CBA), Carbon Footprint, etc. Therefore, joining both capabilities, the developed knowledge-based methodology is addressed to obtaining consistent, objective and arguable data, providing an opportunity to analyze the wide number of possible WWTP configurations, at the same time enabling the integrated assessment of such configurations.

METHODOLOGY DESIGN

The following section describes the three main phases composing the methodology (Figure 1). Three specific procedures support the main steps of the developed methodology. The multidisciplinary information compiled in the

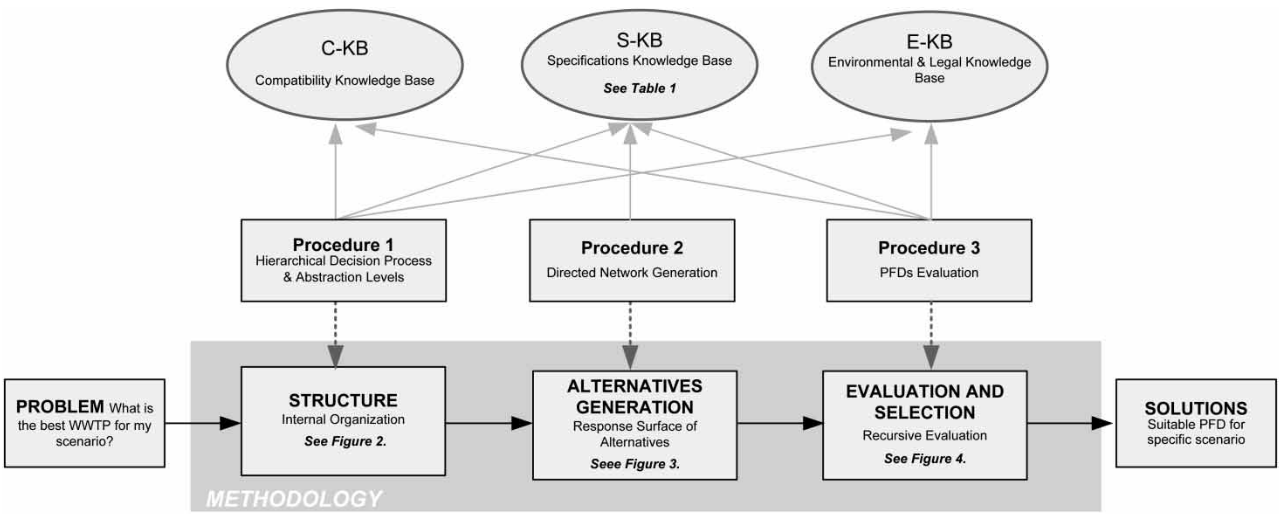

Figure 1 | Methodology scheme.

different knowledge bases (KBs) requires an appropriate management using the procedures. Each procedure gives specific instructions of how data (internal or from the data entry step) have to be linked, related or used through each phase. The first phase includes the methodology structure and how the different KBs composing the system are organized at an internal level. In the second phase the interaction between KBs provides the right framework to generate suitable WWTP configurations. Finally, the third, evaluates in an integrated fashion all suitable PFDs until the selection of the alternatives that meet the specific requirements and user objectives is done.

Design approach

The following section describes the internal design that is used to develop the methodology, which combines the *hierarchical decision process* with the definition of different *abstraction levels*. The *hierarchical* decision process breaks down 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* modify the quantity of detail during the conceptual design practice allowing the decision-maker to be focused on lesser concepts at each time (Lopez-Arevalo *et al.* 2007).

In the presented methodological approach, three abstraction levels are defined: (i) Meta-Units [$MU = E_1, \ldots, E_i, \ldots, E_X$], (ii) Sub-Meta-Units [$MsU = E_{i,1}, \ldots, E_{i,j}, \ldots, E_{i,Y}$] and (iii) Units [$U = E_{i,j,1}, \ldots, E_{i,j,k}, \ldots, E_{i,j,Z}$]. Under this procedures, 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 [MsU] 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.

The encapsulation of the different elements [E] into the Meta [MU], Sub-Meta [MsU] and the Unit [U] level is based on the properties defined by Chittaro *et al.* (1993): (1) structural, i.e. their connectivity, (2) behavioral, i.e. how they work, (3) functional, i.e. role within the process and (4) teleological, i.e. their objective and justification within the process.

In Figure 2, the scheme shows the different units and sub-meta units within the meta-unit treatment of returns coming from the sludge line ($i = 4$, E_4). The range of treatment alternatives moves from Anammox reactors to the storage of the nitrogen-rich returns during day-time and release at night ($E_{4,32,131}$; $E_{4,32,136}$). Therefore, the scheme permits us to check how the level of detail increases from Meta-Unit to Unit level. In an additional example (not shown in the scheme) focused on the secondary Meta-Unit ($i = 2$, E_2), the Submeta-Units composing this level might include Enhanced Biological Phosphorus Removal ($j = 21$, $E_{2,21}$), Attached Growth technologies ($j = 24$, $E_{2,24}$), etc. Then, at the lowest level of abstraction (Units), the scheme would include technologies such as trickling filter, integrated fixed film activated sludge (IFAS), moving bed bioreator (MBBR), biofilter ($E_{2,24,30}$; $E_{2,24,33}$; $E_{2,24,34}$; $E_{2,24,37}$).

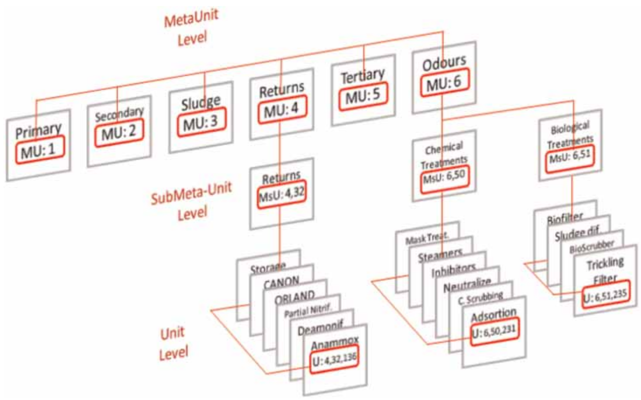

Figure 2 | Graphical representation of the suggested approach. At the highest abstraction level the elements considered are: primary, secondary, tertiary, sludge, odors and return treatment [$MU = E_1, \ldots, E_i, \ldots, E_6$] ($X = 6$). When additional detail is included the elements comprising the meta-unit are increased up to 48 ($Y = 48$). Specifically, if the elements of the Meta-Unit odor treatment ($i = 6$, E_6) are analyzed in detail, two possible Sub-Meta Units can be found: chemical ($j = 50$, $E_{6,50}$) and biological ($j = 51$, $E_{6,51}$) treatments. Finally, at the lowest level of abstraction a list of more than 10 possible alternatives ($E_{6,50,226}$–$E_{6,51,235}$), including scrubbers, neutralizers, trickling filters, bio-scrubbers amongst others, is browsed.

Also the reader can appreciate in both cases 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 behavioral, e.g. neutralization, adsorption, etc.

As a consequence, the level of information is different in the three abstraction levels. The main difference amongst MU, sMU and U is the amount of detail. Thus, at higher levels of abstraction (MU and sMU), KBs are useful to discriminate/screen the alternatives not satisfying the treatment requirements or decision-makers expectations. On the other hand, when shifting to the lower abstraction (S-KB-U), the amount of detail increases substantially and the contained information is used for posterior evaluation.

Knowledge bases (KBs)

The core of the methodology includes three types of KBs. The first KB (S-KB) summarizes the main features of the different treatment technologies, i.e. removal efficiencies, costs, process reliability. The second compatibility knowledge base (C-KB) contains information about the different interactions amongst the treatment technologies and determines which units are compatible with each other, and the third (E-KB) provides legal and environmental information. C-KB and S-KB are replicated for the three aforementioned different levels of abstraction. Thus, the original C-KB and S-KB are in reality: three C-KB (C-KBu, for *Units* level; C-KBsm, for *Submeta-units*; and C-KBm for *Meta-units*) and three S-KB (S-KBu, S-KBsm and S-KBm). The information contained in E-KB mainly focuses on maximum discharge limits and specific constraints from the current legislation considering also different scenarios: discharge in sensitive areas, reuse, sludge disposal requirements, etc. Additionally, economic and environmental aspects are also compiled. The different databases which compose E-KB are meant for the WWTP as a whole. No limitations, for example in legislation terms, are present per unit or group of units. Therefore no different levels of abstraction for this typology of KB are required. In the proposed methodology, E-KB is used to discard PFDs which might not succeed with such criteria. Therefore, a further description is not necessary for the purposes of this paper. However, additional information is available upon request. Expert interviews, specialized literature and engineering experience are incorporated into the KBs. The highly specialized WWTP-related knowledge required to complete such databases has been collected within the NOVEDAR_Consolider project on the collaborative framework of 11 universities, administrations and private companies (www.novedar.com).

Compatibility knowledge bases (C-KBu, C-KBsm and C-KBm)

The C-KB are comprised of unidirectional tables that establish the type of interaction amongst the units composing the PFD. Five types of interactions between unit processes were identified (high compatibility, synergy, low compatibility, potential incompatibility and incompatibility).

Regarding the lower level, *Units*, up to 250 process units within the treatment process have been identified (including innovative and emergent technologies under development), and thus, their whole range of multiple interactions. At *Unit* level a 274×274 matrix (C-KBu) has been designed. Going upward through abstraction levels until *Submeta-Units* (S-KBsm and C-KBsm), 60 groups of technological processes (membrane filtration processes, phosphorous enhancing configurations, etc.) have been included. And finally the six main WWTP parts or *Meta-Units* (S-KBm and C-KBm) compose the upper level.

Specifications of knowledge bases (S-KBu, S-KBsm and S-KBm)

A complete characterization of the identified unit processes and clusters of units compose the S-KBs. At the most detailed and lower abstraction level (S-KBu) at this moment, 274 units are thoroughly characterized by a whole range of parameters (54) encompassed in five main topics, providing the knowledge required in order to obtain suitable PFDs (Table 1). In every process, the following information can be found:

1. *Influent Information*: parameters that define the water quality that can be expected for the unit process in order to perform properly its function within the overall process (maximum admissible flowrate, maximum hydraulic load, presence of grease and oils, maximum chemical oxygen demand (COD), toxic substances, etc.).
2. *Effluent Information*: information about the expected water quality after the unit performance (process efficiencies for a series of pollutants and nutrients, biosolids production, etc.).
3. *Subproducts*: information about the whole range of possible impacts that a WWTP can generate: odors and odor potential, visual impact, etc.
4. *Operation:* data about designing issues and more technical characteristics of the units such as maintenance, process stability and reliability, disturbance frequency, etc.
5. *Costs*: mathematical equations that allow an objective quantification of the main costs in the treatment process (investment, operation costs, energy consumption, maintenance and land requirements). In that topic are also included the required parameters that enable a final CBA for the PFD.
6. *Environmental Impacts:* including all the required parameters needed to carry out the three following analyses: (1) LCA (Baumann & Tillman 2004; Gallego *et al.* 2008); (2) CBA with environmental externality

Table 1 | Shows a snapshot of the 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 some of the parameters characterizing the influent, effluent, economic costs, and operation (Tchobanoglous *et al.* 2003; Comas *et al.* 2004; Ortega de Ferrer *et al.* 2011)

	Anaerobic Lagoon	Wetland (HSCH)	Trickling Bed	Green Filter
Influent				
Population equivalent (p.e.)	150–1500 p.e.	25 –1000 p.e.	200–1200 p.e.	<300 p.e
Hydraulic loading	0.01 – 0.08 $m^3/m^2 \cdot$ day	0.015 – 0.06 $m^3/m^2 \cdot$ day	0.01–0.3 $m^3/m^2 \cdot$ day	0.02 – 0.005 $m^3/m^2 \cdot$ day
Effluent				
DBO elimination (%)	50–85 %	80–90 %	55–95 %	90–99
Costs				
Construction costs	$y = 4617{,}x^{-0.43}$	$y = 3292{,}x^{-0.32}$	$y = 1642{,}x^{-0.22}$	$y = 8966{,}x^{-0.45}$
X: People Equivalent (p.e)	$R^2 = 0.912$	$R^2 = 0.984$	$R^2 = 0.977$	$R^2 = 0.959$
Y: M€	$y = 136.1x^{-0.38}$	$y = 211{,}5x^{-0.40}$	$y = 258.6x^{-0.41}$	$y = 15543x^{-1.32}$
Operation costs	$R^2 = 0.951$	$R^2 = 0.945$	$R^2 = 0.942$	$R^2 = 0.975$
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. Knowledge of agriculture needed

evaluation (Hernández *et al.* 2010); and (3) Carbon Footprint Analysis (theoretical total set of greenhouse gases).

ALTERNATIVES GENERATION

The KB methodology presented in this paper provides a platform able to generate an extensive WWTP alternative response surface according to the treatment requirements and the decision-maker's desires. Such information is represented as a structure in the form of a network (or cluster diagram). As the PFDs are almost unidirectional systems the transformation of the data from first C-KB in a Directed (or Oriented) Network Structure enables the encapsulation of all possible WWTP alternatives in a single figure (Figure 3). The structure is composed of nodes and edges.

1. Nodes represent technologies. Each node is linked to S-KB where the specific properties of the technologies are contained.

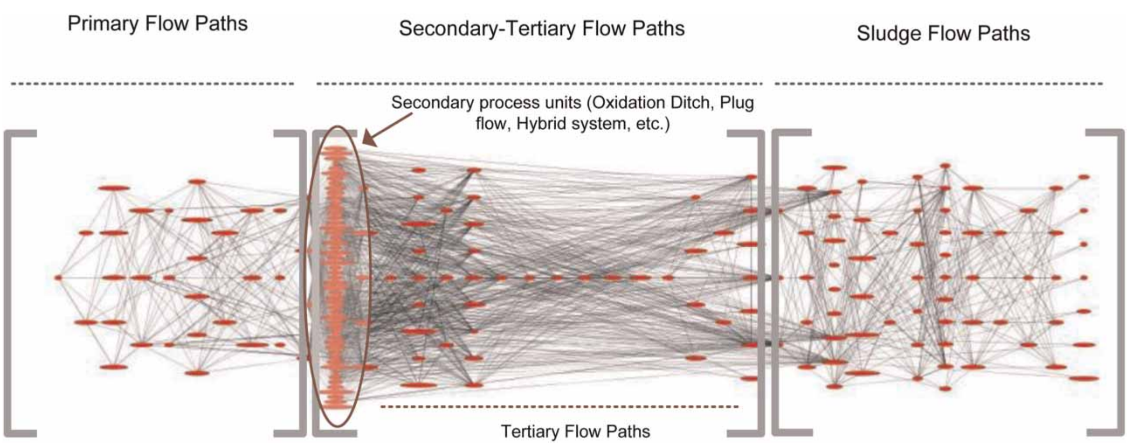

Figure 3 | Example of the Directed Network Structure. Unit processes corresponding to the main three parts (considering secondary–tertiary paths as one) of the WWTP flowsheet are pointed out.

2. Edges represent the connectivity properties between technologies.

PFDS EVALUATION AND SELECTION

When the compatible PFDs have been created, feasible solutions that meet the user overall degree of satisfaction have to be selected. The previously generated Directed Network Structure is used as a functional structure for the transfer of information. The next phase includes the screening, propagation and evaluation of the entire set of PFD alternatives described by the 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 network then becomes a functional system capable of conducting an integrated assessment of treatment trains (Figure 3).

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 step, the multiple technological combinations can be evaluated. Evaluation of each possible diagram relies on the data introduced by the user in the entry step. These data, including influent characteristics, desired effluent parameters and various objectives, must be specified prior to recursive evaluation.

A pre-screening stage is used to simplify the evaluation of multiple alternatives (Loetscher & Keller 2002). This stage is only used for the MU and MsU levels. 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 (Figure 4). Scenario-specific data are modified and used by equations, expressions and other data encompassed in the 54 factors or parameters that define the nodes (technologies) of the diagrams. As said previously, all these factors are linked to the S-KB. 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, do not reach any of the specified user requirements, will be directly removed (i.e. PFDs that do not meet the minimum concentration of phosphorus by legislation when discharging in a sensitive area).

Finally, after the propagation process, each PFD has 54 outputs from the different parameters (e.g. final concentration of contaminants, total investment, and overall bulking risk). The methodology designed supports that each parameter defining the different units might have a user selected factor of prioritization (depending on its objectives and priorities). Thus, for each parameter, depending on the output results of all the possible alternatives generated for any specific scenario, a maximum–minimum range is

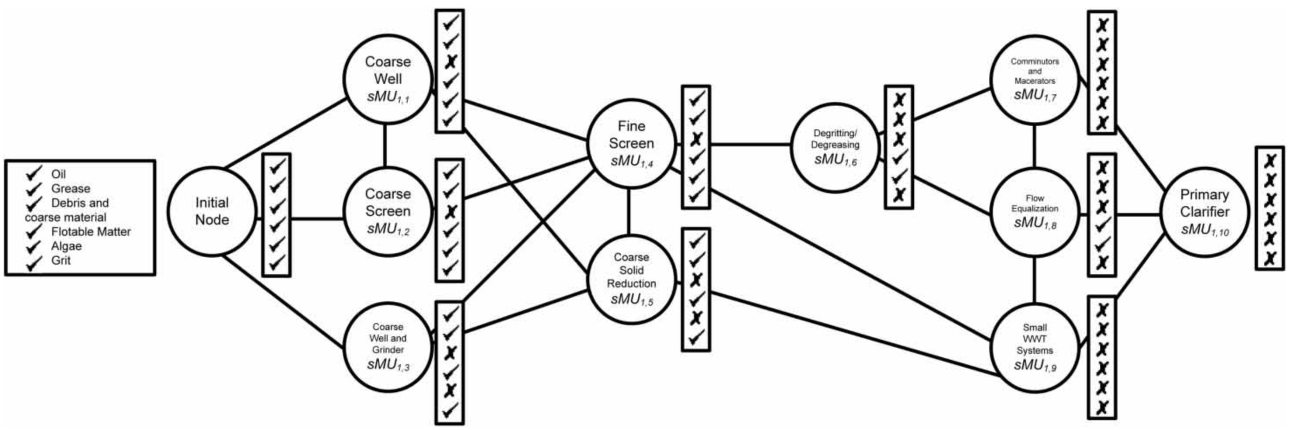

Figure 4 | Simplified representation of recursive evaluation by the Data Processing Module at Sub-Meta Unit Level (S-KBsm). The data introduced for the scenario definition (i.e. initial BOD, pathogenic load, etc.) can be propagated through the structure composed by nodes and edges.

being created in order to generate a comparison framework. In this way, once a value range, enabling the comparison for each parameter, is created, and the prioritization factors are set by the user, the fully characterized PFDs can then be analyzed by a rating algorithm or a Multi-criteria Decision Analysis (MCDA) taking into account the user priorities. The output from analysis of the entire set of embedded treatment trains is generated as a reduced network structure. The DPM then extracts the most feasible alternatives and saves the outputs generated for each PFD in the propagation process. Many methods, including a wide range of MCDA methods, can be used to compare quantitatively the alternatives (Keeney 1982). For example, the Analytical Hierarchy Process (AHP) can be used to compare quantitatively the obtained PFD alternatives (Keeney 1982; Saaty *et al.* 2002; Ashley *et al.* 2008; Flores-Alsina *et al.* 2008). Therefore, the integrated assessment and exhaustive analysis of the alternatives results in the most suitable PFDs for any specific scenario.

CONCLUSIONS

The integrated design of WWTP is a highly complex exercise, which needs to consider the selection of a combination of treatment processes required to achieve the desired effluent quality and a wide range of objectives (from economical and technical aspects to social and environmental ones). The knowledge-based methodology presented in this paper provides a platform able to create suitable PFDs at the same time as providing a methodology for the integrated assessment of treatment trains. The generation of the different flow diagrams is carried out combining databases that contain information about the different treatment technologies and their degree of compatibility

The main contributions of this methodology are:

- Generate the most extensive response surface of WWTP alternatives configurations to explore all possible technological combinations, and avoid the missing of potential solutions that could maximize the plant benefits.
- Offer customized wastewater treatment schemes according to a set of design requirements and initial conditions.
- Facilitate the incorporation of MCDA methods into the treatment train evaluation, allowing an integrated and comprehensive analysis of all the parameters (environmental, social, economic and technical) that modern WWTP should accomplish to deal with 21st century challenges.

Thus, this systematic approach, able to explore the space of WWTP configurations adjusted to user defined conditions, has the potential to accelerate the synthesis and evaluation process during WWTP design.

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