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Development of a DSS for the generation of WWTP configuration alternatives

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Abstract: The objective of this paper is to present the development of a decision support system (DSS) that generates flow diagrams in wastewater treatment plants (WWTP). The proposed DSS is based on a hierarchical decision 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 the flow diagrams is carried out by means of the interaction of two knowledge bases (KB). The first knowledge base (S-KB) summarizes the main features of the different treatment technologies i.e, removal efficiency, costs, process reliability. The second (C-KB) 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 another data-base (E-KB) with additional information about legislation and special requirements. As a result it is possible to further reduce the number of alternatives and finally decrease the size of the design responses surface. The proposed DSS allows the generation of different WWTP flow diagram: i) including conventional and innovative treatment alternatives, ii) exploring multiples technological combinations, iii) avoiding the consideration of treatment alternatives that a high levels of abstraction resulted to be undesirable iv) offering a customized water treatment scheme according to a set of design requirements and initial conditions and v) finally facilitating the incorporation of different evaluation methods to select the alternative that satisfies the most the different design objectives.

Keywords: Alternatives generation, Hierarchical decision, Alternatives response surface, Decision Support System, wastewater treatment plant**,**

1. INTRODUCTION

During the last years, the number of treatment technologies has increased exponentially. This is a response to the demands of society, that every time requires more specific alternatives to satisfy specific needs i.e. water re-use. For this reason the selection of the most suitable alternative in every case is complex. Given this context, powerful decision-making tools are needed to analyze the complexity in the design. *Decision-Support Systems* (DSS) provide such a tool. DSS are capable of supporting complex decision making through an accessible computer interface that presents results in a readily understandable form (Shim et al., 2002; Huang, G.H. 2010). The challenges experienced by planners and designers of wastewater treatment systems include deciding on suitable flow diagrams from a large number of unit process combinations (Chen, 1997), handling of multiple objectives that current WWTP need to satisfy and the goal to achieve socio-economic and environmental sustainability (Poch et al. 2004, Flores et al., 2007). A DSS is inherently integrated, usually consisting of various coupled models, databases, and assessment tools embedded in a graphical user interface (GUI) (He et al., 2006; Li et al., 2001; Matthies et al., 2007; Qin et al., 2006). Therefore, a DSS can be particularly useful in wastewater plant design as it can provide assistance in the selection and evaluation of treatment alternatives before exhaustive simulation or pilot studies are conducted.

2. DESIGN APPROACH

The following section describes the design methodology that is used to develop the DSS. The generation of the alternatives is based on the hierarchical decision process proposed by Douglas (Douglas, 1988). The hierarchical decision process breaks down a complex design problem into a series of issues easier to analyze and to evaluate. In addition, for each one these issues different levels of abstraction are defined (López-Arévalo et al, 2006) reducing and factoring out the design details so that decision maker can focus on a few concepts at a time. Specifically, in this case study, three different levels are created:

1) *Units:* The lowest abstraction level. Each physical technology (or unit process) that can be found in the wastewater treatment (e.g. Primary clarifier, Oxidation ditch reactor, specific advanced treatments, etc.).
2) *Submeta-units:* The medium abstraction level. Set of physical units responsible to accomplish the same function within the process (e.g. Disinfection processes, filtration devices, etc.). However, units clustered in submeta-units have their relevant intrinsic properties (electrical consumption, space requirements, removal efficiency, etc.) that differentiate them and depending on local conditions those feature could made them more suitable than the rest of the technologies.
3) *Meta-units*: The highest abstraction level. At the present time, unit operations and processes within a WWTP flowsheet can be grouped together to provide various levels of treatment (Metcalf and Eddy, 2004). Although several classifications are possible (preliminary, primary, advanced primary, etc) in order to match the DSS objectives have been defined the following meta-units: Primary, Secondary, Tertiary, Sludge, Returns and Odors.

The three levels of abstraction considered for the KBs enable the simplification of the WWTP design problem. Upper abstraction levels reduce the design details so that engineers and plant designers can focus on the most suitable configurations options. Undesirable technological combinations can be factored out at higher abstraction levels making easier the decision making problem. At the same time, when the reduction of not desired flow diagrams is done by decision makers all configurations included on them (at lower abstraction levels) are not going to be taken in account at further evaluation stages, therefore, time and computer sources are saved.

3. SOFTWARE COMPONENTS

The following block describes the different components that compose the developed DSS: The software includes a set of three types of knowledge bases (KB): The first type of KBs summarizes the specifications of the different treatment technologies (S-KB). The other (C-KB) contains the information about their degree of compatibility. Additionally, there is a complementary E-KB with all the information related to legislation and other scenario key aspects (e.i. recommended technologies depending on the scenario, information about evaluation parameters, etc.). Finally, the DSS also includes a data processing module that through KBs interaction enables the generation of the alternatives response surface. Represented as a directed network structure, the generated response surface encompasses all possible WWTP flow diagrams (Up to $1{\cdot}10^7$ depending on the scenario). Finally, different evaluation methods are suggested to select the most desirable alternative according to a set of objectives and criteria.

3.1. Knowledge Bases (KBs)

Expert interviews, specialized literature and engineer's experience are summarized in these KBs characterizing the different technologies and taking into account all their possible physical relations and interactions. Both S-KB and C-KB are replicated for the previously different levels of abstraction. Thus, the original S-KB and C-KB are in reality: Three S-KB (S-KBu, for *Units* level; S-KBsm, for *Submeta-units*; and S-KBm for *Meta-units*) and three C-KB(C-KBu, C-KBsm and C-KBm).

In this way, the wastewater treatment process is represented at several levels of detail. Three graphs clustering the possible flow diagrams shows how the problem can be simplified at higher abstraction levels (Figure 1). At each level of the hierarchy the more or less information about the specifications and the compatibilities is given. The highest level of abstraction (Meta-Units) is composed by the six different main WWTP sections (Primary, Secondary, etc.). Any each section is represented as single "black boxes" with a less detailed characterization, whereas at lower abstraction levels more detailed information is provided. Going downward the following abstraction level is the *Submeta-Units* (S-KBsm and C-KBsm) where 60 groups of processes have been included. And, at the lowest level, *Units* (S-KBu and C-KBu), up to 300 process units within the treatment process have been identified, including emergent and innovative technologies that have been also considered, taking advantage of the aforementioned established relation with experts and research groups involved in wastewater treatment processes.

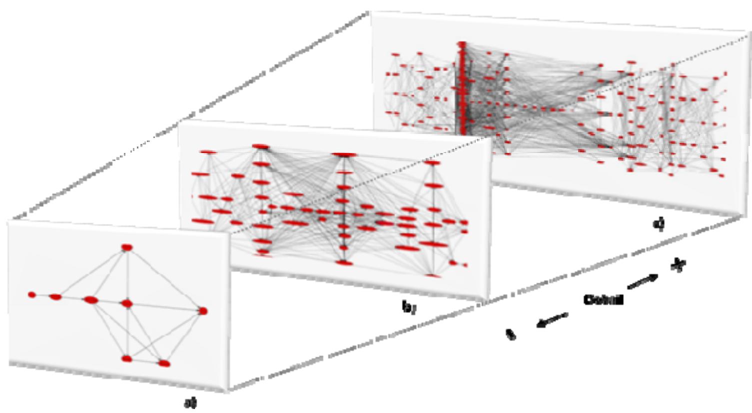

Figure 1. Schematic representation of the three abstraction levels represented as a Directed Network Structures: a) *Meta-units*, b) *Submeta-units* and c) *Units*

3.1.1. Specifications Knowledge Bases (S-KBu, S-KBsm and S-KBm)

A complete characterization of the identified technologies and clusters of them compose the S-KBs. More than 300 unit processes (S-KBu) are thoroughly characterized by a whole range of parameters encompassed in five main topics, providing the knowledge required to obtain the conceptual design of the WWTP. In every process the following information can be found:

1) Influent Information: Parameters that define the water quality expected for unit process in order to perform properly its function within the overall process (presence of grease and oils, maximum COD, toxic substances, etc.).
2) Effluent Information: Information about the expected water quality after the unit performance (process efficiencies for a series of pollutants, nutrients removal, etc.)

3) Impacts/Subproducts: Information about the whole range of possible impacts that a WWTP can generate either from social issues (odors, noises, visual impact, etc.) to environmental aspects as Life Cycle Analysis, Environmental Avoided Impact, etc.
4) Operation: Data defining designing issues and more technical characteristics of the units such maintenance, process stability, problem frequency, etc.
5) Costs: Mathematical equations that allow an objective quantification of the main costs in the treatment process (Investment, Operation costs, Energy consumption, etc.)

Upper abstraction levels are also characterized following the previous division of topics. However, the characterization differs significantly from the *Units* level, and an adapted version for their characterization has been done. Both levels have been highly simplified and they do not consider any type of quantitative data. Only qualitative information about functional aspects is included, defining their degree of suitability to confront specific scenario situations. I.e. discarding equalization tanks in situations where the flow variations are not relevant.

3.1.2. Compatibility Knowledge Bases (C-KBu, C-KBsm and C-KBm)

The C-KBs are unidirectional tables establishing for each technology which type of interaction corresponds with the rest of WWTP-related technologies. Six types of interactions between technologies were identified (Precondition, high compatibility, synergy, low compatibility, potential incompatibility and incompatibility). Such information is contained in three matrixes corresponding to the previously defined levels of abstraction (6x6, C-KBm; 60x60, C-KBsm; and 300x300 in the case of the C-KBu).

The developed DSS is designed to extract the contained information in the three matrixes and transform the acquired knowledge in an interconnected group of technologies (or cluster of technologies). The resulting group is then represented as a structure in the form of a network (or cluster diagram). And, as the wastewater treatment plants are unidirectional systems, the network structure that fit best to that kind of process is the Directed (or oriented) Network Structure (Figure 2). Such kind of structure allows the representation of all possible diagrams within the structure without repeat any unit that is involved in other diagrams.

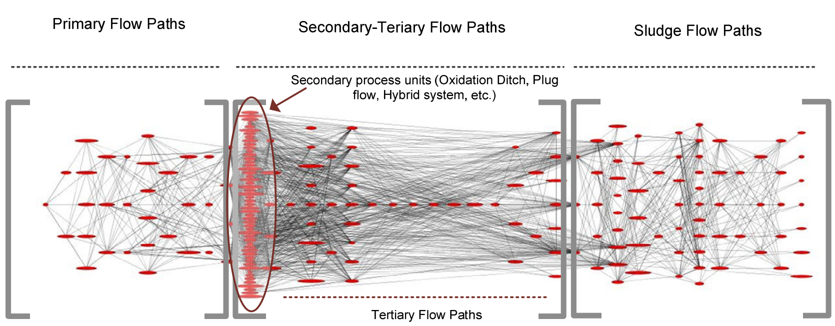

Figure 2. The Directed Network Structure built from the compatibility knowledge base (C-KBu) representing in a single cluster diagram all the possible WWTP alternatives diagrams. Unit processes corresponding to the main four parts of the WWTP flowsheet are pointed out.

The created networks structure from the respective C-KBs is then used to: 1) generate the whole response surface of possible alternatives and, therefore, represent all the possible WWTP alternatives flow diagrams; and 2) construct a suitable structure base where carry out the evaluation of treatment trains at further stages. In that way, the created flow paths between technologies (represented as nodes) can be used as functional connections that are able to send information from one node to another. Therefore, by means of a data processing module the constructed structure have the capacity to transfer, transform and manage different data in order to carry out an integrated evaluation (Figure 3).

Thereby the response surface of possible flow diagrams is expressed as a directed network structure (Figure 2) where nodes (technologies) and edges (interactions) compose the structure:

(1) Nodes in the network structure include the knowledge acquired about their specifications. A linkage between the represented technology (node) with the external knowledge base (S-KBu), where the specific knowledge of each unit is contained, allows the consideration of the properties of each individual technology when an evaluation method is applied.
(2) On the other hand, edges represent technologies interactions and their connectivity properties with other treatment processes. Also, when further flow diagrams evaluation are going to be carried out the edges properties can be analyzed in order to obtain several "node centralities" to measure its relative importance within the network (Freeman, 1978). Therefore, node centralities can be used and obtain a more integrated and exhaustive evaluation of the flow diagrams (Bañarés-Alcántara, 2009) 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).

3.1.3. Complementary Knowledge Base (E-KB).

Additionally, there is a complementary KB with all the information related to legislation and other scenario key aspects such as recommendations of technological combinations depending on the scenario, data needed for the quantification of some parameters, etc. The E-KB is linked to KBs, S-KB and C-KB. Different issues about legislation, technical details, etc. have to be taken in account during the treatment design. Therefore, a KB encompassing this relevant information has been created to provide the required knowledge during the different steps that compose the conceptual design and the evaluation of flow diagrams. Data about parameters and water contaminant legislation for the different types of effluent discharges and effluent reuse are collected in this KB. Also, other information that is optionally used about emergent contaminants concentrations, odors, pathogens, parameters evaluation and other legislative and environmental issues are contained

3.2. Data processing module

The data processing module has been designed to support the evaluation of the multiple technological combinations contained within the created network structure. The exploration of these multiple flow diagrams is possible by means of the combination of the network relationship properties with the data processing module.

As mentioned previously, when the evaluation of possible diagrams is needed, the created structure can became a functional system were the connections (or edges) between nodes can be used to establish data paths where data can be transferred (Figure 3). The data processing module is responsible to detect the large number of alternatives embedded on the network and extract them as single flow diagrams ready for being evaluated. Then, the assessment of the multiple technological combinations can be carried out.

For the evaluation of each possible flow diagram is necessary to take in account the influent, the desired effluent and the different objectives in order to evaluate the alternatives performance to such specific conditions. Therefore, in any evaluation data entry is required in order to introduce data defining the initial conditions or scenario.

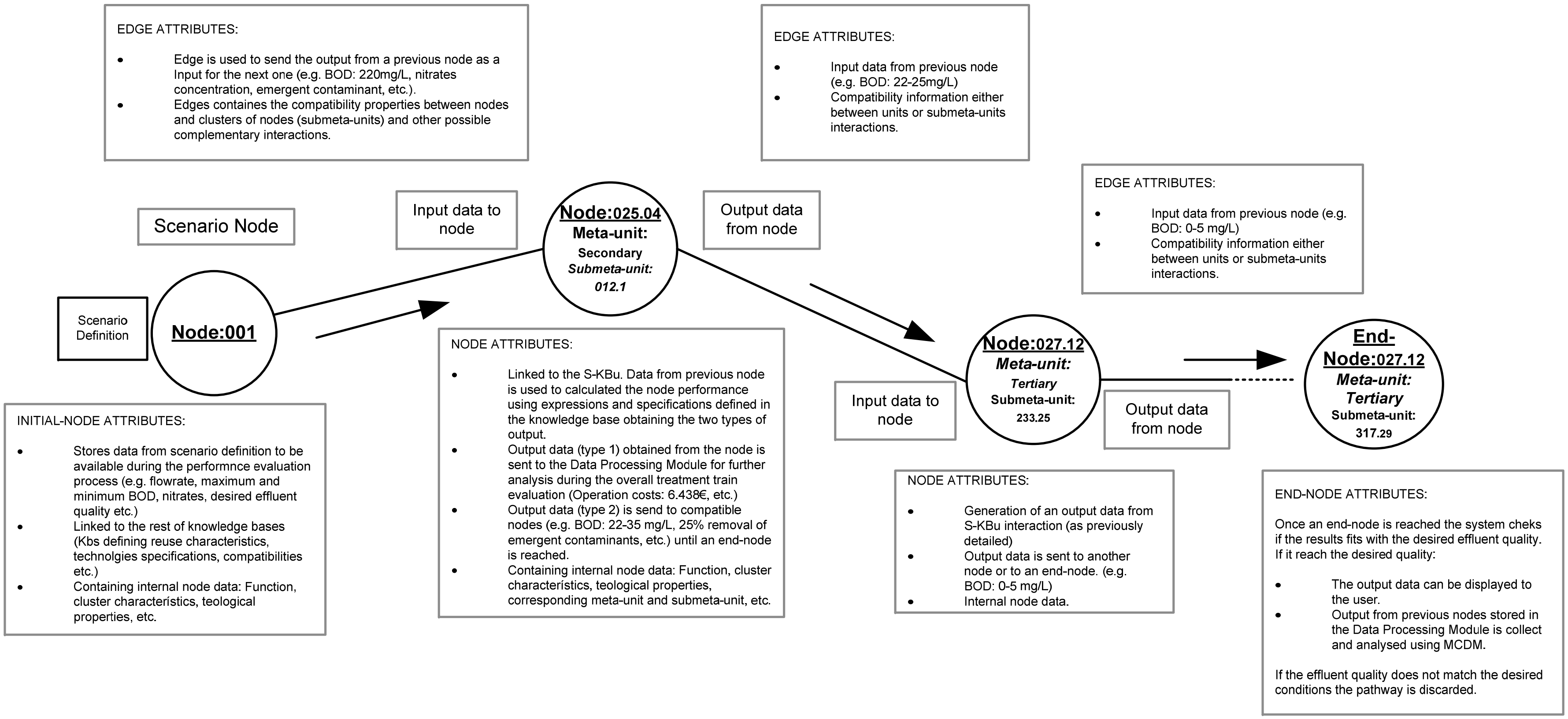

Figure 3. Schematic representation of the Directed Network Structure data transfer and evaluation process.

In that way, once the data entry has been introduced into the DSS, the data processing module saves and manages this information. Then, the introduced information is transferred to every flow diagram extracted in the previous step. Therefore, the data passes through the combination of the different nodes composing every single flowdiagram. During the evaluation the information interacts with each node (because every single node is linked to the S-KB containing information, expressions and other data about the specific technology performance) and, an output obtained from that interaction is then generated. Later on, as the data processing module saves the resulting output from every node in any treatment line is possible to assess its overall performance, and even carry out comparisons with the rest of analyzed flow diagrams.

4. GENERATION OF A SCENARIO-ADAPTED RESPONSE SURFACE

Previous sections have shown that is possible the generation of the whole WWTP alternatives response surface. If no limitations are taken in account a large number of feasible technological combinations ($1\cdot10^9$) is obtained. Nevertheless, the large number of possible flow diagrams difficult the evaluation of the every obtained alternative within this response surface. Moreover, many of the possible alternatives certainly would not match to designer objectives or specific scenario conditions. . Therefore, the reduction of the number of possible alternatives is of the outmost priority. Considering only the most promising alternatives could simplify, and make less time consuming, the evaluation of the alternatives, becoming easier the finding of the most suitable solutions.

As said, many of the alternatives obtained could not match to the decision maker requirements or objectives. So, a discarding process able to factor out such technological combinations to reduce potential solutions has to been done. Such process is carried out by taking in account the data entry used to define the scenario.

Nevertheless, still many possible flow diagrams can satisfy (but at different degrees of satisfaction) the predefined scenario conditions and user objectives. Thereby, according to the introduced information during the data entry the non-discarded alternatives can be assessed the treatment train performance in economical, technical, social and environmental terms.

As said in previous sections, the information introduced during the data entry is transferred to every single flowdiagram to allow the evaluation. Then, every unit process within the flowdiagram through its unique characteristics and expressions generates an output that can be divided in two different types of data. This data is the main responsible of the discarding process. The first type, not directly related with the data processing module, represents contaminants removal efficiencies and water quality properties along the treatment process. Following the aforementioned procedure, the output data is sent from one node (unit process) to the next compatible node of the flowdiagram as an input. This next node, depending on their own function or properties, will modify again the received input to an output that can be used for the next unit process in the treatment train, and this process goes further within the WWTP alternative until the water quality predefined in the scenario definition is achieved. The second type of output data, also generated from the interaction between the scenario input and the unit characteristics (e.g. total electrical consumption, required space, LCA, etc.), is stored in the data processing module. So, every single node composing the WWTP configuration saves the obtained results in the module for further integrated analysis. And later on, the processing module is responsible to manage the previously saved information and offer the results of the evaluation.

Finally, multi-criteria decision methods could be implemented in order to enable quantification of the overall degree of satisfaction of different design objectives and rank the different alternatives to finally find the most suitable WWTP alternatives depending on the specified scenario conditions. Furthermore, complementary simulation platforms, Cost-benefit calculations, etc. could improve the evaluation and assessment process going on step forward: from the conceptual design to the detailed design.

5. CONCLUSIONS

This paper has presented the development of a DSS to support the conceptual design of WWTP generating multiple treatment schemes. A hierarchical methodology considering different levels of design abstraction breaks down the WWTP design problem into a series of issues easier to analyze and to evaluate. The generation of the response surface of WWTP alternatives is carried out combining two data bases that contains information about the different treatment technologies and their degree of compatibility. As a result, it is possible to obtain treatment customized treatment schemes according to the user preferences using a step-wise procedure

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