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Application of a support system to the design of wastewater treatment plants

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Abstract

This paper presents a case study that explores the advantages that can be derived from the use of a design support system during the design of wastewater treatment plants (WWTP). With this objective in mind a simplified but plausible WWTP design case study has been generated with KBDS, a computer-based support system that maintains a historical record of the design process.

The study shows how, by employing such a historical record, it is possible to: (1) rank different design proposals responding to a design problem; (2) study the influence of changing the weight of the arguments used in the selection of the most adequate proposal; (3) take advantage of keywords to assist the designer in the search of specific items within the historical records; (4) evaluate automatically the compliance of alternative design proposals with respect to the design objectives; (5) verify the validity of previous decisions after the modification of the current constraints or specifications; (6) re-use the design records when upgrading an existing WWTP or when designing similar facilities; (7) generate documentation of the decision making process; and (8) associate a variety of documents as annotations to any component in the design history.

The paper also shows one possible future role of design support systems as they outgrow their current reactive role as repositories of historical information and start to proactively support the generation of new knowledge during the design process. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Design; Wastewater treatment plant; Support systems; Environment; Software

Nomenclature

BOD:	biochemical oxygen demand (mg O_2/l)
Bx:	sludge loading rate (Kg BOD/d Kg MLVSS)
hrt-av:	average hydraulic retention time (h)
hrt-max:	maximum hydraulic retention time (h)
MLVSS:	mixed liquor volatile suspended solids (mg/l)
P:	total phosphorus (mg/l)
Q_{max}:	maximum flow rate (m^3/d)
Q_{av}:	average flow rate (m^3/d)
SS:	suspended solids (mg/l)
TKN:	total Kjheldal Nitrogen (mg/l)
tvss:	sludge retention time (d)
V:	Volume (m^3)
VSS:	Volatile suspended solids (mg/l)

1. Introduction

The increasing concern regarding the destruction and pollution of our environment has produced a growing worldwide awareness of the need for more effective Wastewater Treatment Plants (WWTPs). The main goal of a WWTP is to reduce the pollution level of urban and industrial wastewaters, prior to discharge to the environment.

These wastewaters, containing basically solids, organic matter, nutrients and oils, are treated in successive stages inside the WWTP. First, there is a pretreatment stage, where the influent wastewater is prepared for further treatment by removing debris, sand, rocks, gravel, etc. Then, a primary treatment separates the ready settleable and floatable solids from the wastewater. Finally, a secondary treatment that involves biological treatment reduces soluble biodegradable organic matter from the wastewater. The main biological technology applied is the activated sludge process, where wastewater and a multispecific population of microorganisms are first combined, mixed, and aerated in a bioreactor. After enough time is given for the biological reactions to

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Table 1
Sample engineering design support systems and their perspective and application domain

System	Perspective	Domain of application
PHIDIAS and HOS [9]	Argumentation Communication	Computer networks
GMTD [10]	Argumentation	Aircrafts
ADD and ADD+ [11]	Documentation Communication	Offshore oil platforms
KBDS [12]	Argumentation Documentation	Chemical processes
DRIM [13]	Argumentation Documentation	Software systems

take place (microorganisms use the organic matter and the available oxygen as their substrate), the contents of the reactor are transferred to a separate settling basin. At this stage, the wastewater can be discharged to the environment or, when required, treated further with an advanced method.

As a side effect, WWTPs generate a large amount of a byproduct called sludge (basically a liquid mixture of microorganisms and particulate organic matter), which must also be treated. Thickening, stabilisation, and dewatering are the main unit operations that convert the sludge into a stable product for ultimate disposal [1].

A proper operation, combined with a suitable plant design, guarantees a successful WWTP performance. In particular, the design of a WWTP is especially complex due to some specific characteristics such as the high variability of the inflow wastewater (both in quantity and quality), the lack of understanding of the biochemical process, and the large amount of subjective and uncertain knowledge used during its design. Furthermore, the engineer must acknowledge a set of objectives to meet present and future demands in terms of water quality requirements, operational reliability, and minimum construction and operation costs. Thus, the design of a WWTP has to assume various complex objectives, many in clear contradiction, such as minimising costs while creating safe and operative installations that provide completely reliable wastewater treatment.

Another complicating factor is that regulatory, community and national standards are always subject to change. This is also true for the cost of some of the key inputs to the process, e.g. the price of a kilowatt-hour, a cubic metre of oxygen, or a square metre of land may fluctuate significantly with time. Designer decisions are, therefore, subject to a series of variable constraints conditioning the most appropriate WWTP design. This applies particularly in the retrofit of an existing WWTP.

Literature offers a large amount of useful textbooks with theoretical considerations for appropriate WWTP design e.g. Refs. [1,2]. Similarly, many mathematical models and empirical correlations [3–5] have recently been published to facilitate WWTP design tasks, including some prototype computer-based design packages [6,7] which allow greater speed and accuracy.

However, to gain maximum benefit from computer support, designers and operators must have future access to the design rationale (the decisions that were made, the justifications behind them and the alternatives considered together with the reasons for rejecting them), i.e. a corporate memory of design decision making. In principle, design rationale maintenance and use can not only improve the current design process, but also the interpretation and reusability of previous designs.

Thus, the focus of this paper is to highlight the potential advantages of working with a computer-based support system that maintains a record of the design process when designing a WWTP, not to describe any mathematical model that improves the final WWTP process. In consequence, the suggested advantages are independent of the correlations or models chosen to dimension the equipment. KBDS [8], a prototype design support system for integrated and co-operative chemical process design, was chosen as the demonstration vehicle as it has a number of desirable features allowing a substantial improvement of the design process. Although KBDS has been previously tested on different chemical processes, this is the first time that it is applied to an environmental system.

A number of prototypical design support systems (DSS) for different areas of application have been presented in the literature. A sample is presented in Table 1. It should be mentioned that the work of the several research groups working in DSS development is a continuum spanning from the purely theoretical (e.g. knowledge representation) to the applied (e.g. design re-use), and can focus on one or more of the following perspectives:

- Argumentation, for example in the representation of argumentative discourse.
- Documentation, as in the maintenance of a decision trail.
- Communication, to study information sharing among members of a project team.

To our knowledge, however, none of the existing DSS architectures has been tested in the important application area of WWTPs. Furthermore, the ideas described in this document have already found industrial applications. In particular, some specific characteristics of KBDS have inspired the development of DRAMA [14], a commercial system which has been tested in the nuclear and chemical industries, the results of these applications being proprietary. Consequently, this paper should be read as a description of the capabilities of KBDS within the framework of an important application area.

The paper is structured as follows: Section 2 briefly describes KBDS and its previous applications, while Section 3 presents the scenario of WWTP design, explaining some of the different objectives, alternatives, models, rationale and keywords recorded into KBDS. Section 4 shows in detail the main advantages of maintaining the design history records in KBDS and, finally, Section 5 summarises the main results shown throughout the paper.

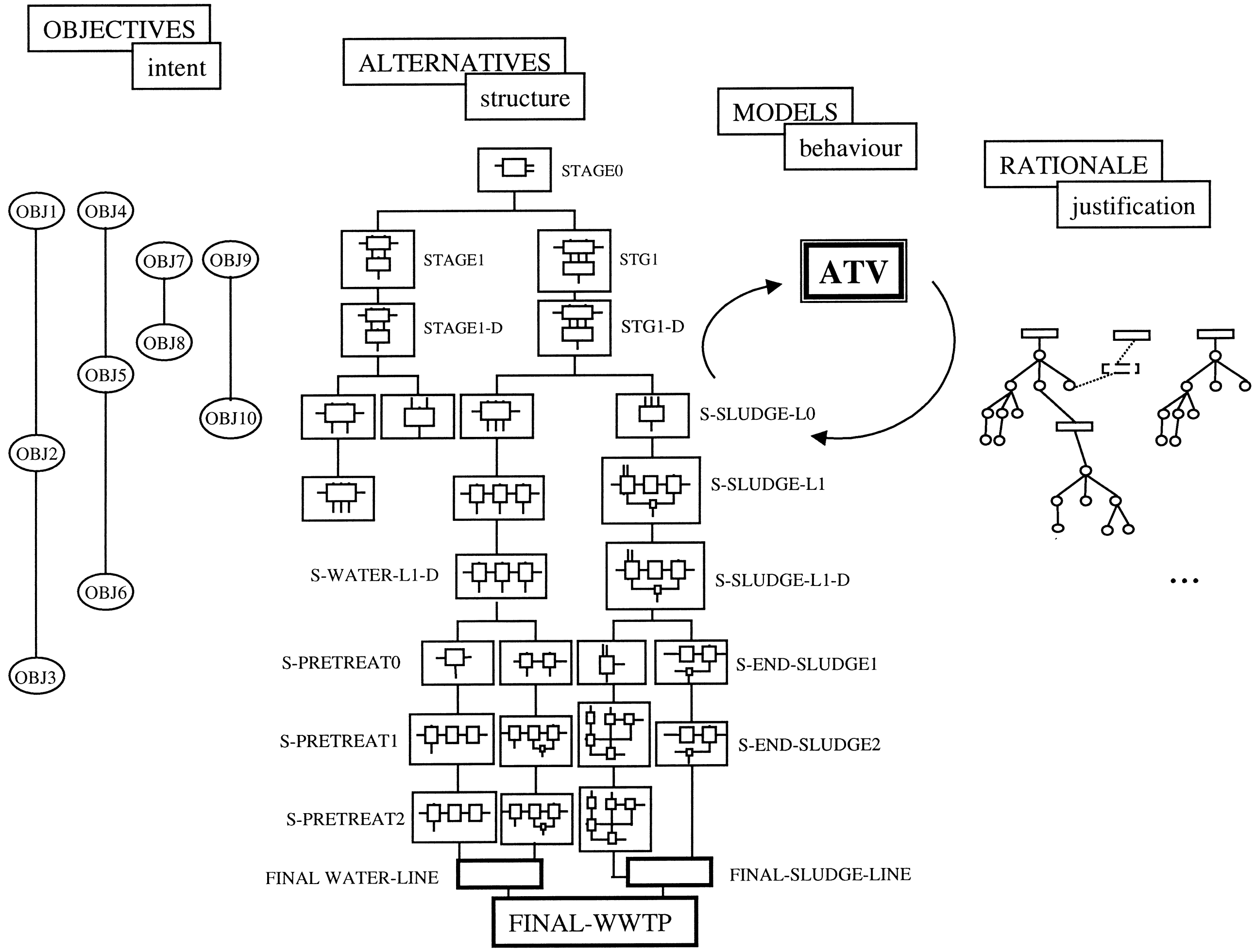


Fig. 1. KBDS description of the design process in terms of four interrelated networks.

2. Background to KBDS

KBDS is a design support system for the conceptual design of chemical processes. It is able to record and use not only a description of the chemical process as it is evolved by the designers (plant subsystems, design parametres and operating variables), but also parts of the history of the design process itself, i.e. its objectives, decisions and their rationale.

KBDS has been tested on an experimental basis on a number of different types of processes:

- Hydrodealkylation of toluene (an example of a large, continuous, single product process) [8,15].
- Hydrofluoric acid (an example using a rigorous steady state model in ASPEN$^+$ and proposing a plausible design history to generate an existing process) [12,16].
- Methyl acetate (exploring the possibility of design re-use for similar processes, i.e. for ethyl, isopropyl and propyl acetates) [17].
- Penicillin (an example of a small, batch process) [18].
- Nuclear engineering application (proprietary information of BNFL).
- Safety analysis of tanks storing flammable materials (proprietary information of QuantiSci).

A design process is represented in KBDS by means of four interrelated networks that evolve through time:

- One for the design objectives, with specifications and constraints (see Section 3.1);
- another for the design alternatives (see Section 3.2);
- a third one for design rationale (see Section 3.3);
- a last one for the models of the design alternatives (see Section 3.4).

Fig. 1 shows these four interrelated networks corresponding to the case study presented in this paper.

KBDS has a graphical user interface which displays the design *objectives* space in the form of a network of objectives. Each objective consists of one or more constraints or specifications that the final design must meet. The function of the interface is to ease the declaration and modification of design objectives, with designers able to navigate, locate, retrieve and operate upon any of its parts. This implies that design objectives in KBDS are not fixed, but evolve through time, thus allowing for the refinement of a set of initial design objectives which may be inconsistent, redundant, incomplete or ambiguous.

A structure similar to the design objectives history is used in the design *alternatives* space, where each node in the network represents a design flowsheet or scheme. Each scheme may have one or more operational alternatives, i.e. a single flowsheet structure may have more than one set of design variables (and thus a different behaviour for each).

A useful design support system must also have access to the appropriate design information, calculations and procedures, such as databanks, physical property prediction methods and simulation engines. The design *models* space contains the models used to predict the behaviour of the design alternatives.

There are two types of relations between design objectives and alternatives: generation and evaluation. Design alternatives are generated to try to satisfy the design objectives, and in turn, satisfaction of the objectives is evaluated in terms of the predicted behaviour of the design alternative (via the design models). Multiple objectives may be maintained, allowing the evaluation of any design alternative with respect to any subset of design objectives.

The fourth network represents the design *rationale* and records the design deliberation, argumentation and decision justification by means of IBIS (Issue-Based Information Systems) networks [19], each representing a design issue and its solution. IBIS networks can store every design decision along with its competing options and the set of arguments used in the final selection. The design rationale is intimately related to the design alternatives history maintained by KBDS via three mechanisms: an IBIS network is proposed in response to a problem or a question related to a design alternative or one of its parts; in turn, the rationale may use constraints placed on the design alternatives to give backing to the arguments used in the selection of options; lastly, once an issue has been resolved, it gives rise to the step that transforms a design alternative into its successor in the design history.

Once the design history has been recorded by the user and is accessible in the computer, it has a number of potential uses:

- *Re-design and re-use:* KBDS can identify which parts of the chemical process must be re-designed should there be a change in an assumption, constraint or specification. It can also determine from what point in the design history the review needs to take place. Both features play an important role in the selection of the parts of the chemical process that can be re-used in the face of similar (but not identical) design objectives and constraints.
- *Automatic evaluation of positions:* Arguments can be given a weight and uncertainty values which may be used to rank positions in order of relative desirability. Weights may be assigned a temporary value to allow “what-if” studies to be undertaken.
- *Automatic report generation:* Reports describe the evolution of the design alternatives and the associated argumentation during the decision making process. Documentation of the design process is important because it is the only form of communication of the corporate memory outside the design team.
- *Search:* During the design of a chemical process a large number of issues will be raised, addressed and resolved. To assist the designer in tracing these decisions it is useful to have a method of indexing such records. KBDS can associate one or more keywords to each of the design rationale nodes. Keywords correspond to important design concepts and may have associated words, i.e. either synonyms, names of equipment which perform a related task or any other words related to the keywords in any other sense. The dictionary of keywords is user-defined and specific to each design project.

3. Scenario of a WWTP design

A simplified but plausible WWTP design has been generated with the support of KBDS. The case study corresponds to a plant that must treat urban wastewater from a city with 30,000 equivalent-inhabitants (e-inh.), with stable population, and without a significant industrial contribution. To estimate the maximum wastewater flow rate ($Q_{\max}$) and its contamination level, we have followed the recommendations of a local environmental engineering firm related to one of the authors. It has been assumed that there is a daily average contribution of 250 l/e-inh., containing 75 g of organic matter (measured as BOD), 90 g of Suspended Solids (SS), 9.5 g of nitrogen (measured as TKN), and 3 g of phosphorous (P). The maximum rate of contaminants has been calculated with a security factor of 1.5, and $Q_{\max}$ has been estimated following the empirical equation [20] (where Q_{av} is the average flow rate):

$$Q_{\max} = Q_{\mathrm{av}}\left(1.15\,\frac{2.575}{Q_{\mathrm{av}}^{1/4}}\right)$$

The next sections show how designers have stored in KBDS the design objectives, alternatives, rationale, and models for the WWTP in the case study.

3.1. Design objectives

The main objective of any WWTP is to meet the quality limits fixed by law in order to reduce the impact on receiving waters. In addition, designers must also comply with other objectives, such as those related to operational reliability (e.g. the mechanical equipment must be robust and simple) and minimum construction and operating costs, while maximising beneficial reuse of products and minimising odours and disturbances for the neighbouring cities.

Although all of these objectives have been considered

Table 2
Set of quality objectives defined for the WWTP design

OBJ1 comply with the limits fixed by the European regulation 91/271/CEE for water discharge
$\xrightarrow{\text{refine}}$ OBJ2 OUTFLOW ($SS < 35$ mg/l; $BOD < 25$ mg/l)
$\xrightarrow{\text{refine}}$ OBJ3 OUTFLOW ($SS < 35$ mg/l; $BOD < 25$ mg/l; $TKN < 10$ mg/l; $P < 1$ mg/l)
OBJ4 comply with the limits fixed by the European regulation 91/271/CEE for sludge disposal
$\xrightarrow{\text{refine}}$ OBJ5 dewater and stabilise sludge
$\xrightarrow{\text{refine}}$ OBJ6 SLUDGE (water $< 75\%$; $VSS < 40\%$)

during the case study design process, we will focus the paper examples on those that are concerned to meet the quality standards fixed by law. New European regulations (91/271/CEE) set discharge levels for the treated water (suspended solids, organic matter, and nutrients) and for the sludge disposal (water and volatile percentages). Table 2 shows this initial set of objectives and their evolution during design.

During design, the initial objectives OBJ1 and OBJ4 are refined by the designers into numerical constrains that are expressed in terms of the variables defined in the design alternatives. Thus, for example, the first objective (OBJ1), written in English and stating that the WWTP outflow must comply with the limits fixed by law, can be refined and expressed quantitatively as OBJ2. This is possible because the variables present in OBJ2 and corresponding to Suspended Solids and Biodegradable Organic matter at the outflow (SS and BOD) were defined in the design alternatives proposed after OBJ1 was specified. European legal criteria fix the quality objective for large WWTP effluents as $SS < 35$ mg/l and $BOD < 25$ mg/l. If later in the design it were recognised that this plant discharges to potentially eutrophication waters, it would also be necessary to treat nutrients. Thus, OBJ2 would in turn be refined to OBJ3 by adding the regulation limit for dumping nitrogen and phosphorus to the receiving water ($TKN < 10$ mg/l and $P < 1$ mg/l). A similar refinement was applied to OBJ4, concerning the European legal limits for sludge disposal, resulting in OBJ5 and OBJ6.

Expressing the objectives in terms of equalities or inequalities allows the designer to evaluate, at any time, a proposed design alternative with respect to any of the objectives, checking whether the values of the variables of an alternative satisfy the desired objectives.

3.2. Design alternatives

The design of the WWTP flowsheet or scheme is defined by the user in KBDS by means of the design alternatives

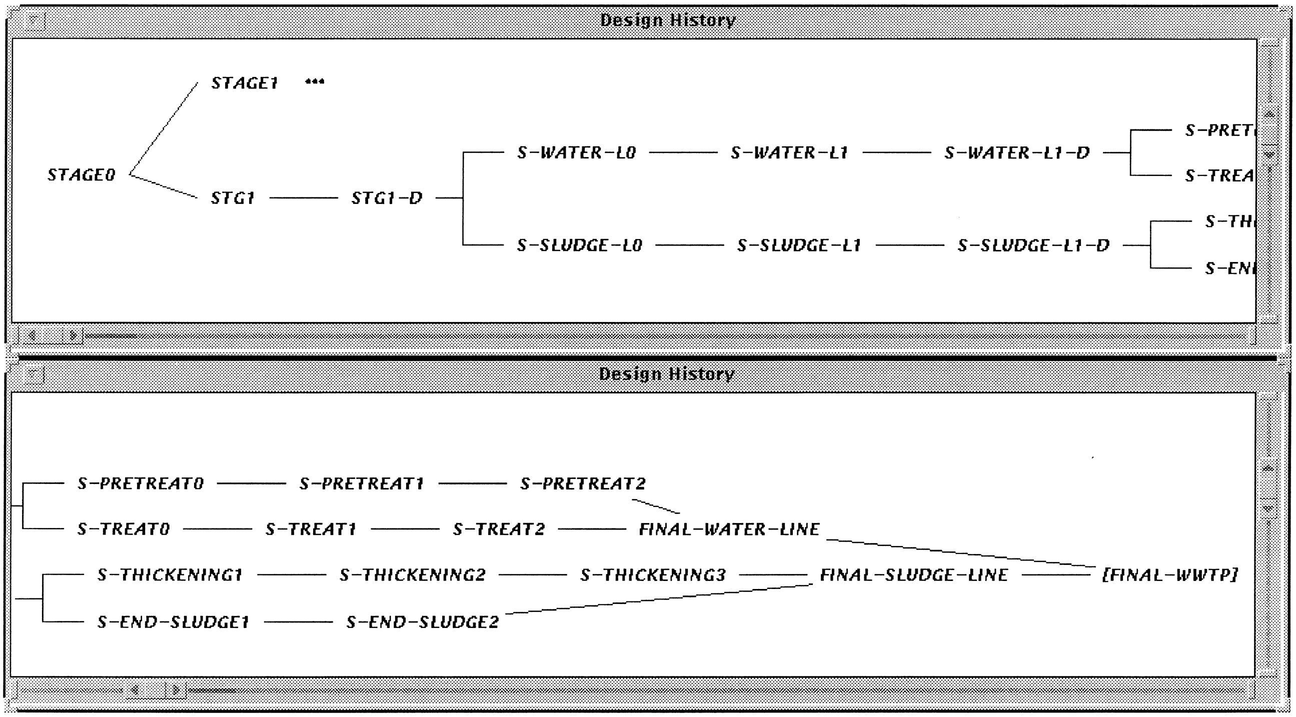


Fig. 2. Schema hierarchy (design history) for the WWTP design case study.

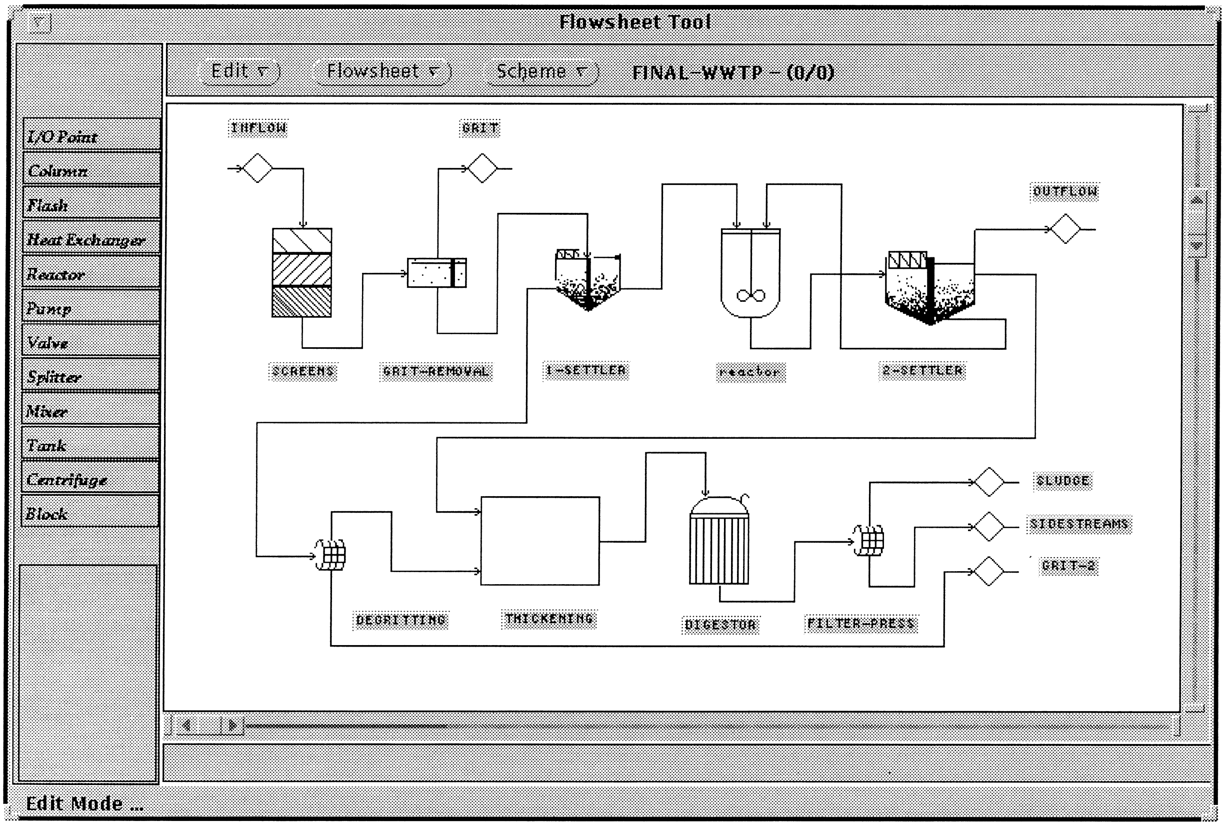


Fig. 3. Structure of the final flowsheet of the WWTP design case study.

space. Both, schemes and alternatives, also evolve as the design unfolds.

Initially, the designer may only have an abstract idea of the process, thus specifying the WWTP as a “black-box”, i.e. a process whose function is defined, but whose structure has yet to be determined. This initial scheme must then be evolved and, when convenient, partitioned into new partial schemes that simplify their design. In this way, separate design teams can concentrate on the design of just one part of the project. However, partitioning a scheme does not mean its parts become independent, because any change affecting the connecting streams is automatically reflected in both partial schemes. Fig. 2 shows, in the form of a hierarchy, the different intermediate schemes and the final result of the WWTP design case study. For space reasons, the complete design history is split in two windows. The figure shows the following features of the design history:

- straight lines depict how a partial design is evolved through refinement and revision steps (for example from STG1 to STG1-D);
- node branching “ $<$ ” indicates paths to competing design alternatives (STAGE0 was evolved to STAGE1, the designer backtracked, and then STG1 was created);
- the ellipsis “…” indicates that a further design branch exists but is not shown in the window (in our example STAGE1 evolves into a dead-end branch of the design and the user has toggled off its depiction);
- a design can be partitioned into two or more subsections, this operation is represented by the node decomposition operator “[“ (e.g. STG1-D is split into S-WATER-L0 and S-SLUDGE-L0);
- node merging “ $>$ ” indicates that two partial design are joined into one (e.g. FINAL-WATER-LINE and FINAL-SLUDGE-LINE are merged into FINAL-WWTP).

The Design History window in the figure shows the flowsheet design evolution, from STAGE0 to the final scheme proposed, called FINAL-WWTP (shown in Fig. 3). Its structure differentiates two main lines, one for the wastewater and the other for the generated sludge. The water line has three main steps: pretreatment (consisting of bar screens, an aerated grit chamber and flow measurement), primary treatment (circular settlers), and secondary treatment (an activated sludge process with a stirred tank bioreactor and circular secondary settlers). The sludge line has also three main steps: thickening (degritting and gravity tanks for primary sludge; dissolved air flotation for secondary sludge), stabilisation (an anaerobic digestor), and dewatering (pressure filter presses). Each one of these units has different operational alternatives, which will be detailed in Section 3.4.

Deciding which units need to be included in each of the

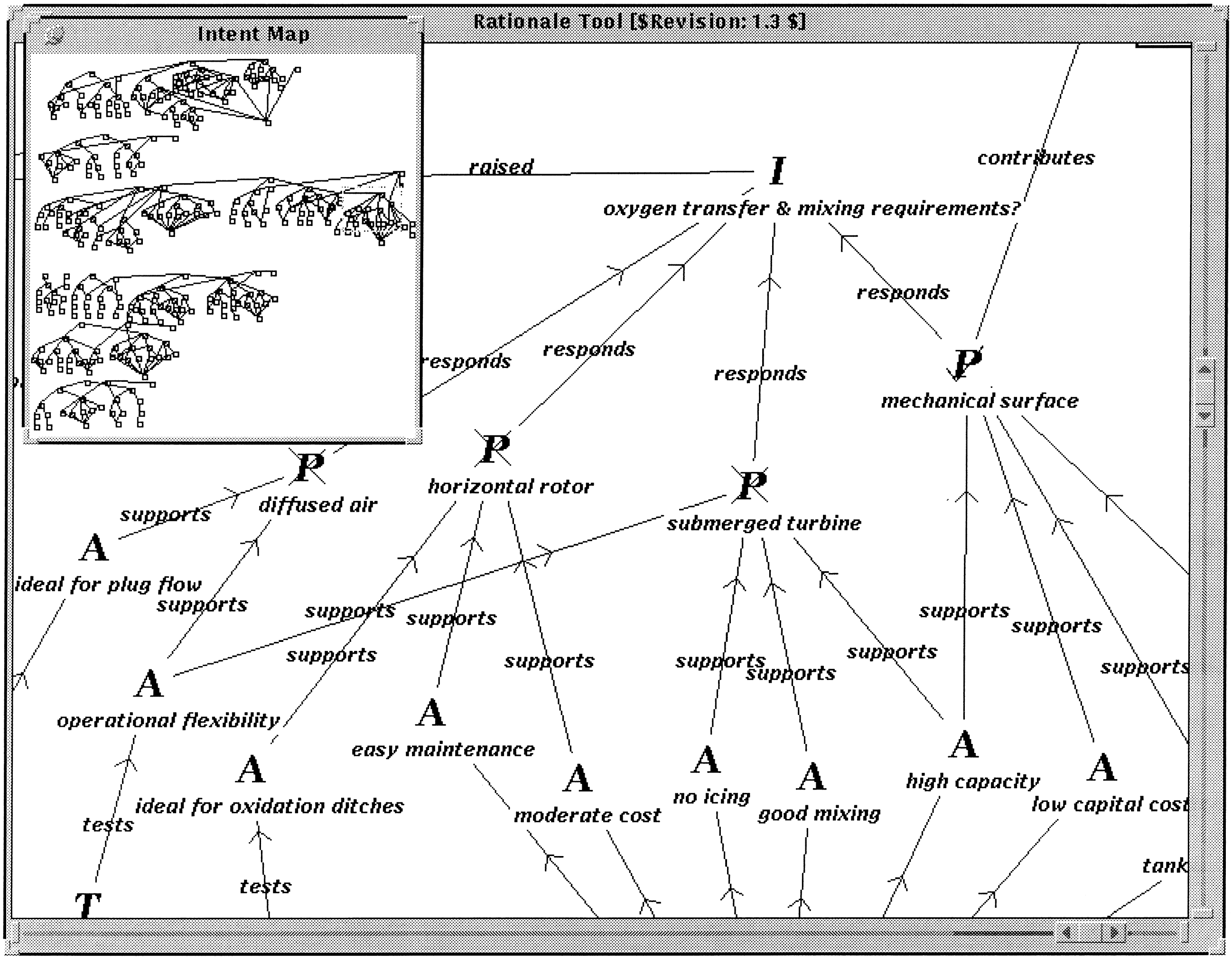


Fig. 4. IBIS network for the issue *Oxygen transfer and mixing requirements*?

WWTP lines is not straightforward, but is the result of deciding on a series of questions or issues, each having a variety of different possible solutions or positions. Each issue has been solved following a decision-making process, which is recorded by the designers in the rationale space of KBDS.

3.3. Design rationale

The design rationale space records the rationale, deliberation and argumentation processes. Their importance resides in the fact that a proper analysis of the design process must consider the rejected as well as the selected alternatives. Only then can the designer appreciate the whole scope of the design. Furthermore, if parts of a design are to be re-used in future designs, the designer must be familiar not only with options that were considered and the final decisions, but also with the justifications for their selection and with their limitations.

Fig. 4 shows how this information has been included by the designers as an IBIS network in the design rationale space. The example refers to the question or issue *Oxygen transfer and mixing requirements*? that links four different positions or alternatives with their associated arguments behind or against the selection of a position. The supply of oxygen to suspended biomass represents the single largest energy consumer in an activated sludge facility. Over the years, oxygen transfer equipment has evolved enough to give an engineer a wide selection of devices to meet the specific needs of a facility [1]. Due to the different impact of the supporting arguments for a given position, KBDS allows the designer to associate a weight to each argument indicating its relative importance, thus enabling the ranking of positions by taking the relative importance of the arguments into account.

This simple network represents the 17th issue raised during design, and deals with the selection of oxygen transfer and mixing equipment to be used in the WWTP. Four possible types of equipment are considered (positions): a mechanical surface turbine (the one that was eventually selected), a submerged turbine, a horizontal rotor and an equipment to diffuse air. In turn, the positions are compared

Table 3
Main options considered for the design of the WWTP water-line (part 1)

Originating scheme	Issues	Positions	Resulting scheme
S-WATER-L0	I3: include primary treatment?	*Yes*/No	S-WATER-L1
	I4: include advanced treatment?	*Yes*/No	
S-PRETREAT0	I5: include grid removal?	*Yes*/No	S-PRETREAT1
	I6: include flow equalisation?	*Yes*/No	
S-PRETREAT1	I7: screening equipment?	*Screens*	S-PRETREAT2
		Comminutors and grinders	
	I8: cleaning equipment?	Manually	
		Mechanically	
	I9: grid removal equipment?	*Aerated grit chamber*	
		Vortex type	
		Detritus tank	
		Horizontal flow type	
		Hydrocyclone	
	I10: Flow metre?	*Flumes*	
		Weirs	
		Tubes	
S-TREAT0	I11: primary treatment equipment?	Fine screens	S-TREAT1
		Imhoff tanks	
		Sedimentation tanks	
	I12: preaeration chamber?	Yes/*No*	
	I13: chemical coagulation chamber?	Yes/*No*	
	I14: biomass media?	*Suspended-growth system*	
		Attached-growth system	
		Combined system	
		Dual biological treatment	
S-TREAT1	I15: shape of the settler?	Stacked	S-TREAT2
		Circular	
		Rectangular	
	I16: aeration basin configuration?	*Complete mix*	
		Oxidation ditch	
		Plug flow	
		Sequencing batch reactor	
		Specific modifications	
	I17: oxygen transfer and mixing requirements?	Diffused air	
		Mechanical surface	
		Horizontal rotor	
		Submerged turbine	

in terms of the following criteria (arguments): design and operation flexibility, capital cost, plant capacity, mixing, splashing, maintenance and suitability for reactor configuration.

The collection of IBIS networks raised during the design process form the global network of the design rationale, an overall view of which appears in the top-left corner of Fig. 4, and is labelled the Intent Map.

Although there is no space herein to present each issue in detail, the main design issues and their associated positions are summarised in Tables 3 and 4, with the selected positions appearing in italics.

3.4. Design models

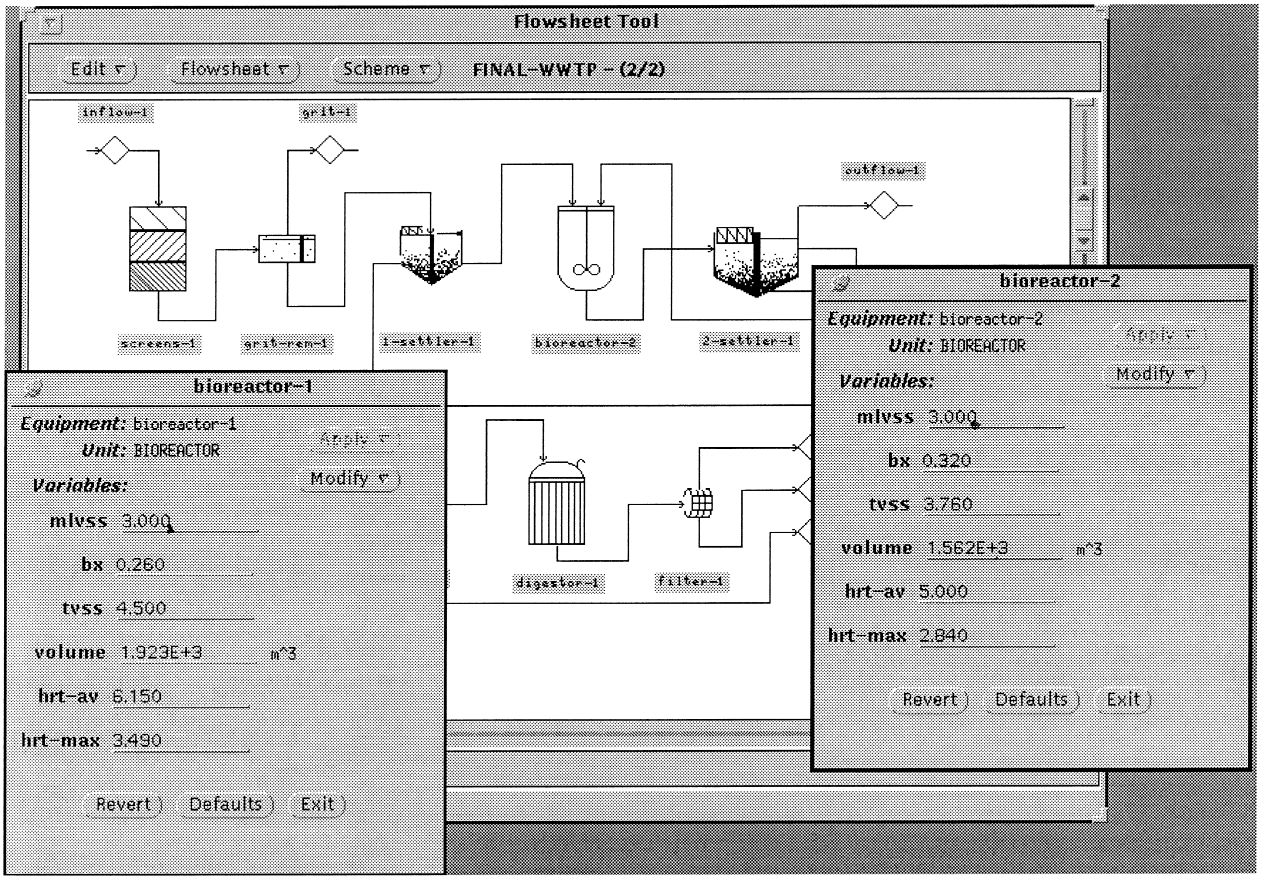
Diverse design alternatives can be generated for each scheme by using different values for the design variables. Two different design alternatives have been created to dimension the main units included in the final WWTP scheme (see Fig. 3). They result from choosing two different models to design the final WWTP flowsheet: ATV standards [21], and some proprietary empirical correlations from an environmental engineering firm.

Although it is not the goal of the paper to explain in detail the sizing of all the units, Fig. 5 shows, as an interesting example, the alternatives generated for the bioreactor, resulting from the two different models.

While the first alternative (bioreactor1) fixes the Mixed Liquor Volatile Suspended Solids (MLVSS) and sludge retention time (tvss) as operational parametres, the second alternative (bioreactor2) is based on MLVSS and Sludge Loading Rate (Bx). As can be seen, this discrepancy results in different bioreactor volumes and hydraulic retention times (hrt). The difference is due to the application of two

Table 4
Main options considered for the for the design of the WWTP sludge-line (part 2)

Originating scheme	Issues	Positions	Resulting scheme
S-SLUDGE-L0	I18: include primary treatment?	*Yes*/No	S-SLUDGE-L1
S-THICKENING1	I20: join sludge streams?	Yes/*No*	S-THICKENING2
	I19: sludge degritting?	Primary *Yes*/No Secondary Yes/*No*	
S-THICKENING2	I21: thickening method for primary sludge?	*Gravity* Dissolved air floatation Centrifugal Gravity belt thickener or Rotating drum thickener	S-THICKENING3
	I22: thickening method for secondary sludge?	Gravity *Dissolved air floatation* Centrifugal Gravity belt thickener or Rotating drum thickener	
S-END-SLUDGE1	I23: stabilisation treatment?	*Anaerobic digestion* Aerobic digestion Composting Lime addition	S-END-SLUDGE2
	I24: dewatering method?	Centrifuge dewatering *Belt filter presses* Pressure filter presses Natural methods	



Equipment: bioreactor-1
Unit: BIOREACTOR
Variables:
mlvss 3.000
bx 0.260
tvss 4.500
volume 1.923E+3 m^3
hrt-av 6.150
hrt-max 3.490

Equipment: bioreactor-2
Unit: BIOREACTOR
Variables:
mlvss 3.000
bx 0.320
tvss 3.760
volume 1.562E+3 m^3
hrt-av 5.000
hrt-max 2.840

Fig. 5. Different alternatives generated for the bioreactor.

Table 5
Sample of keywords used during the WWTP design process

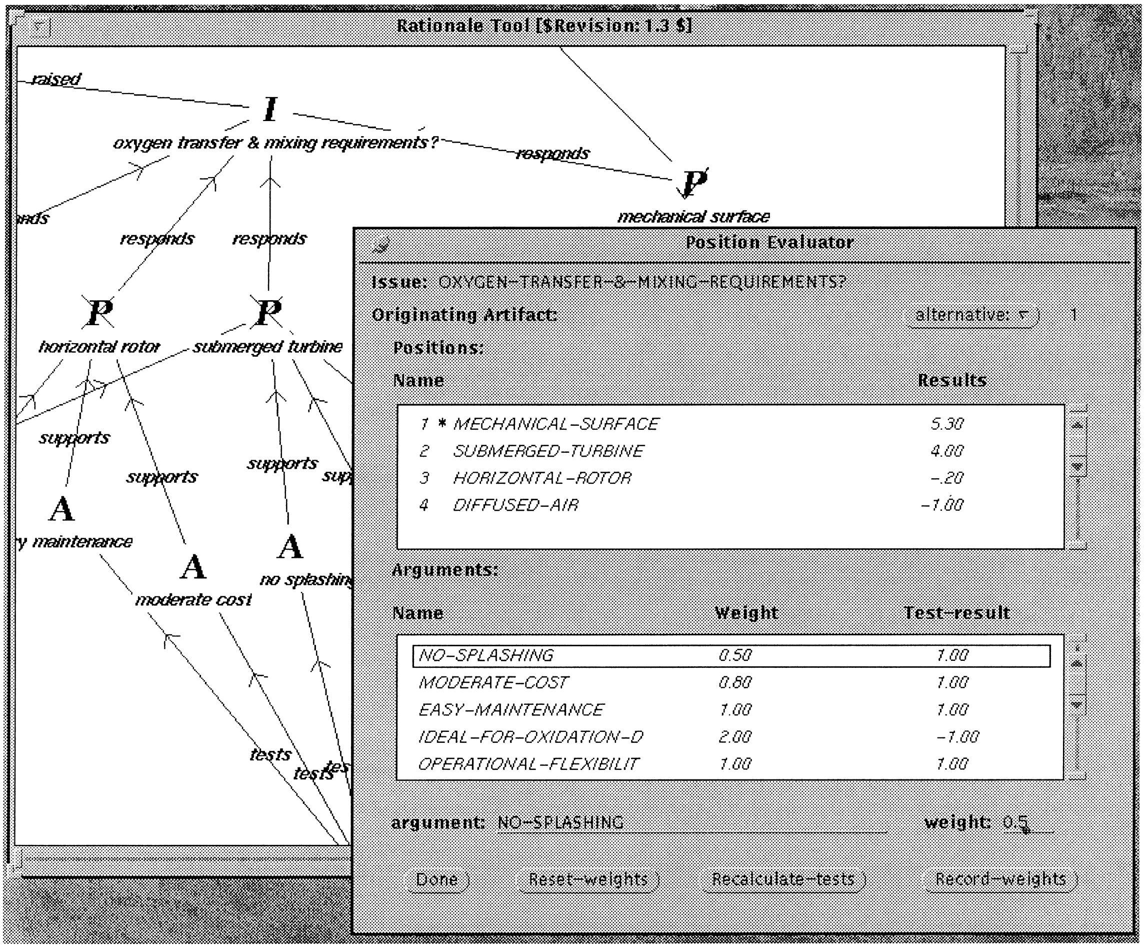
Structure	Function	Other
Water-line	Operational-functions	Installation
Pretreatment	Screening	Maintenance
Screening	Flocculation	Operation
Screens	Preaeration	Operational-problems
Bar-screens	Thickening	Floating-materials
Mechanically-cleaned-screens	Sludge-settling	Clogging
Manually cleaned-screens	…	Odour
Grinders	…	Abrasion
…		…
Grit-removal		
Aerated-grit-chamber		Operational-variables
…		Oxygen-demand
Flow-equalisation		Energy-consumption
Flow-measurement		BOD
Flumes-flowmetre		…
…		
Primary-treatment		Constraints
Primary-settler		Size
…		Space
Secondary-treatment		Flexibility
Bioreactor aeration-basin		
Suspended-growth-reactor		Product-quality
Plug-complete-mix-reactor		Stable-product
…		Agricultural-use
Secondary-settler		Industrial-use
Sedimentation-tank		…
…		
Advanced-treatment		
Sludge-line		
Thickening		
Sludge-degritting		
Gravity-method		
…		
Primary-sludge-stream		
Join-sludge-streams		
Secondary-sludge-stream		
Join-sludge-streams		
Stabilisation		
Anaerobic-digestion		
…		
Dewatering		
Pressure-filter-presses		
…		

alternative empirical correlations during the design, and points to another of the advantages of KBDS, namely, that it lets the designer record and follow more than one promising alternative during the design. This feature has the potential to improve the final design (by allowing the designer to explore a larger portion of the design space) and reduce the number of trial and error design iterations (carrying more than one alternative at a time means that the designer does not have to commit to a decision while information is incomplete).

3.5. Indexing and search of the design records

During the design of a complex artifact many thousands of objects of diverse nature will be created and linked, e.g. process flowsheets, models (equations, variables and their values), textual documents, etc. An effective design support system must be able to allow easy navigation and search of the resulting networks. For example, finding at what point in the design history a particular subject was discussed, whether a problem has been addressed and resolved, or whether similar topics have been considered in the current or previous projects.

KBDS achieves the above by categorising design objects according to a user-defined set of keywords, one or more of which can be associated to each of the nodes in the design history. The underlying assumption being that, since the keywords have a meaning and semantic relations to each



Issue: OXYGEN-TRANSFER-&-MIXING-REQUIREMENTS?

Originating Artifact: 1

Positions:

Name	Results
1 * MECHANICAL-SURFACE	5.30
2 SUBMERGED-TURBINE	4.00
3 HORIZONTAL-ROTOR	-.20
4 DIFFUSED-AIR	-1.00

Arguments:

Name	Weight	Test-result
NO-SPLASHING	0.50	1.00
MODERATE-COST	0.80	1.00
EASY-MAINTENANCE	1.00	1.00
IDEAL-FOR-OXIDATION-D	2.00	-1.00
OPERATIONAL-FLEXIBILIT	1.00	1.00

argument: NO-SPLASHING **weight:** 0.5

Fig. 6. Ranking of positions for the issue *Oxygen transfer and mixing requirements*?

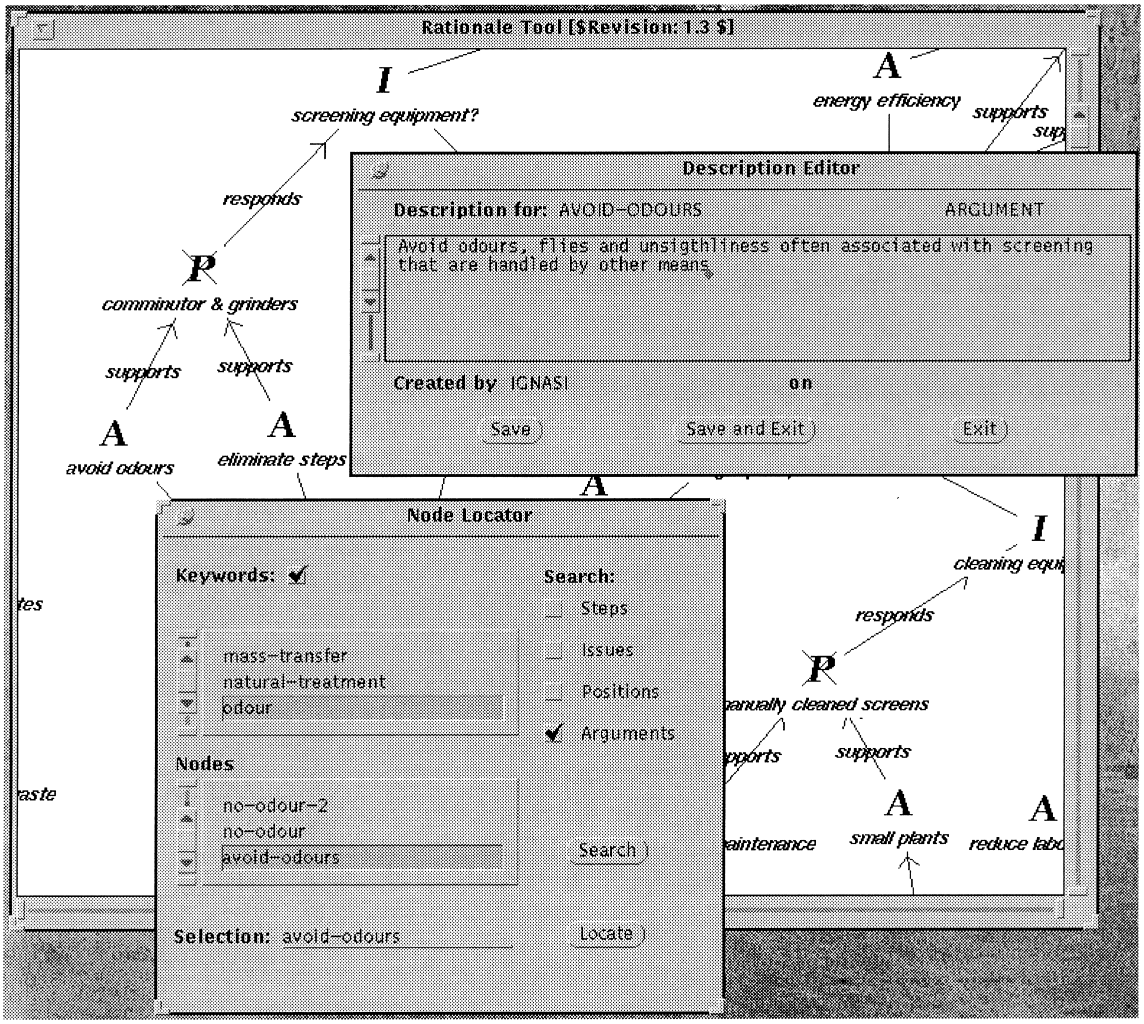
other, they can be used not only as indices during search, but also as an indication of the relations between the objects they categorise. Although the assignment of keywords to nodes can be carried out manually, one should not completely depend on this, since the resulting assignments could be incomplete (due to lack of time on the designer's part) or erroneous (due to an absence or misrepresentation of the node properties).

Resulting from the above, initial categorisation in KBDS is carried out semiautomatically using a simple word-matching technique similar to the one used in Ref. [22] and spelling checker programmes such as UNIX spell [23]. Words in the object name, its description and any other associated textual documents are matched against those in a dictionary containing keywords and associated words. These last may be either synonyms, names of similar concepts, or any word related to the keyword in any other manner. For example, the user may propose "separation" as a keyword and "settler", "clarifier", "flotation", and "chemical precipitation" as associated words. While the dictionary is generated entirely and a priori by the design team, the automated categorisation mechanism is domain independent.

Additionally, keywords can be used by KBDS to determine whether all the topics raised by a problem (issue) have been covered by the proposed solutions (positions) and their justifications (arguments). In practical terms, this automates the discovery of some inappropriate rationale structures, missing keywords and missing nodes.

Both mechanisms, the semiautomatic categorisation and the rationale consistency, are explained in more detail in Ref. [12].

In the instance of the WWTP case study design process, the authors of the paper identified more than 150 keywords. It was soon realised that many of these keywords were not independent, but could be organised into several groups reflecting the diverse contexts from which an object can be understood, e.g. from the point of view of the structure of the plant, its operation, the quality of the final product, environmental and safety constraints, etc. Table 5 shows a selection of keywords organised in a hierarchy, where the indentation of the keyword is proportional to its specificity, e.g. "bar-screens" are one type of "screens", which are items of equipment used in "screening", which is a task done during "pretreatment", which in turn is a stage of the "water-line" section of the WWTP.



Rationale Tool [$Revision: 1.3 $]

Description Editor

Description for: AVOID-ODOURS ARGUMENT

Avoid odours, flies and unsigthliness often associated with screening that are handled by other means

Created by IGNASI on

Node Locator

Keywords: ✓

mass-transfer
natural-treatment
odour

Nodes

no-odour-2
no-odour
avoid-odours

Search:
☐ Steps
☐ Issues
☐ Positions
☑ Arguments

Selection: avoid-odours

Fig. 7. Node locator searching for the keyword *odour*.

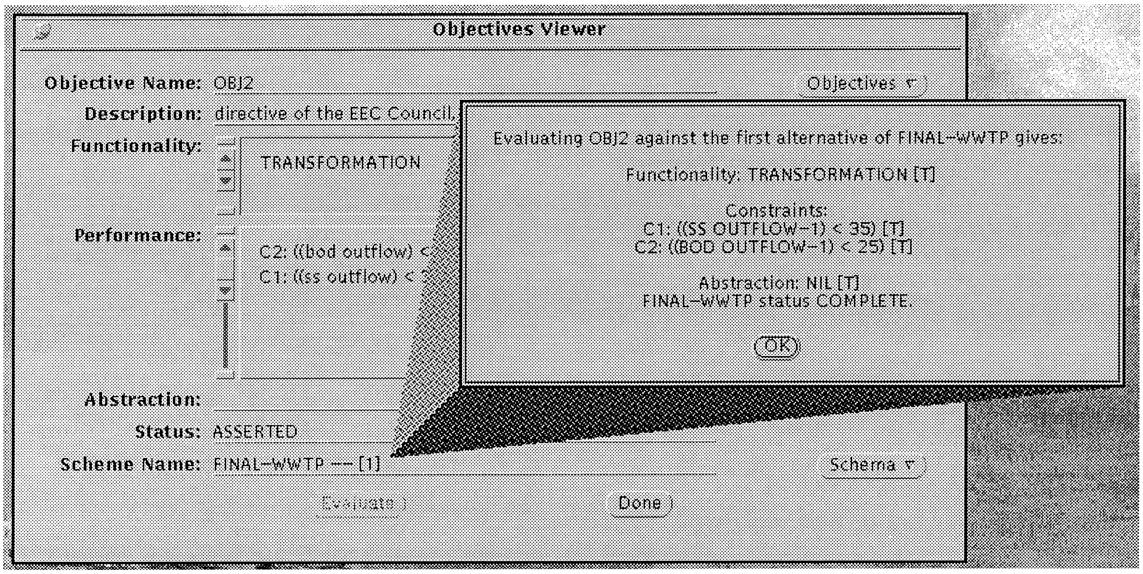
4. Advantages derived from the design history records

As the design process proceeds, the objectives, alternatives and rationale are being recorded in KBDS by the design team. This section discusses some of the potential advantages of recording the design history in the WWTP case study, and illustrates them in terms of specific examples.

4.1. Automatic ranking of positions

Section 3.3 explained how it is possible to associate a different weight to each argument thus indicating their relative importance in the support of a position and enabling the ranking of the positions responding to an issue. As an example, Fig. 6 shows the Position Evaluator window on the Rationale Tool corresponding to the issue *Oxygen transfer and mixing requirements*? (see the corresponding IBIS network in Fig. 4). This particular issue is answered by four different and competing positions that resolve the oxygen transfer and mixing for the bioreactor.

The selected position is “mechanical surface aerator” (marked with an asterisk), while “submerged turbine” is the second most promising. “Horizontal rotor” and “diffused air” are ranked as the third and the fourth option. This ranked list of positions is calculated using the list of supporting arguments, their weight, and the result of evaluating the associated tests. Tests are a measure of the degree to which the design alternative that raises an issue complies or not with the statement of an argument, in our example, to what degree the oxygen transfer and mixing equipment does not splash, has a moderate cost, easy maintenance, etc. The overall score for each position is the sum of the products of the weight times the result of the associated tests. In the present application the result of the test is 1 when the argument is true or implies an advantage, and the result is -1 when the argument is false or implies a disadvantage, but it is possible to return fuzzy values in an evaluation within KBDS. The score of the selected position is clearly positive (5.30), but the position considering “submerged turbine” is very close (4.00), while the two other options are far from the chosen solution (-0.2 and -1.0).



Objective Name: OBJ2
Description: directive of the EEC Council,
Functionality: TRANSFORMATION
Performance: C2: ((bod outflow) <
C1: ((ss outflow) <
Abstraction:
Status: ASSERTED
Scheme Name: FINAL–WWTP –– [1]

```
Evaluating OBJ2 against the first alternative of FINAL–WWTP gives:

Functionality: TRANSFORMATION [T]

Constraints:
C1: ((SS OUTFLOW–1) < 35) [T]
C2: ((BOD OUTFLOW–1) < 25) [T]

Abstraction: NIL [T]
FINAL–WWTP status COMPLETE.
```

Fig. 8. Result of evaluating OBJ2 against the first FINAL-WWTP operational alternative.

4.2. "What-if" studies

Sometimes the designer wishes to study the effect of changing the weight of some arguments to evaluate their influence in the final choice. This is especially advisable in the example mentioned above, with two closely ranked positions responding to the same issue. Assigning temporary values to the weights of the arguments allows the designer to undertake "what-if" studies. For example, assume that the weight of the argument NO-SPLASHING is increased from 0.50 to 2.00, in order to try and avoid health and environmental problems caused by spreading untreated water. A new ranking of the positions using the Position Evaluator window would show the positive influence of this argument on the submerged-turbine position, whose recalculated result would be 5.50, and would thus appear as the most promising position over the mechanical surface aerator. The designer must then decide which one of the two options is the most suitable. The weights assigned to the supporting arguments may or may not correspond with the actual choice, but at least they expose the arguments interaction and will provide a record of the designer's priorities.

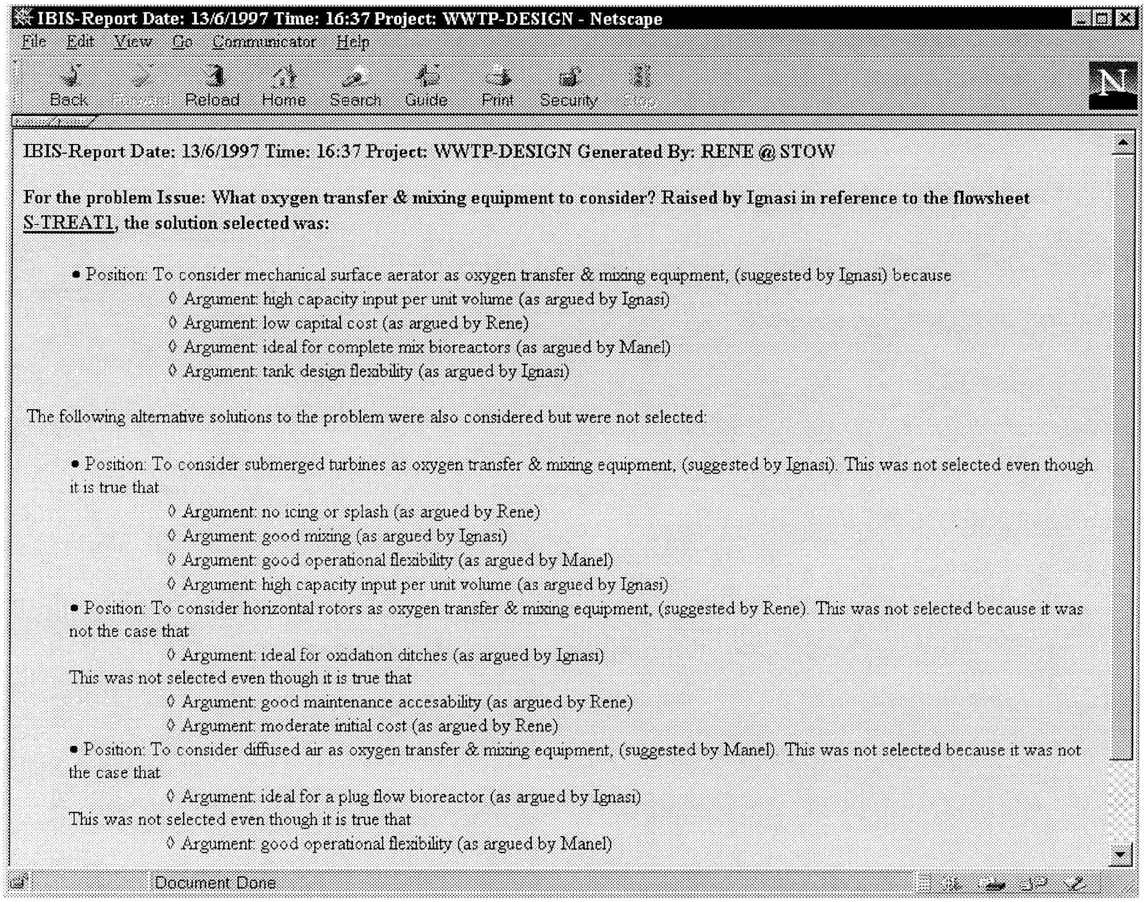
4.3. Use of keywords during search of the design records

The following situation exemplifies the advantages of associating keywords to each of the design rationale nodes. Assume that the design team finishing the sludge line of the WWTP case study has a crucial discussion regarding the potential existence of odour problems. Offensive odour can be originated in this line if the sludge is treated with certain types of units that appear as possible choices to the issues in the sludge line (see Table 4). To evaluate the extent to which this factor has been taken into account during the global design of the plant, the designers decide to examine each previous node to see whether the odour argument has been considered while designing the different parts of WWTP design. As shown in Fig. 7, the Node Locator allows the user to search among all the rationale nodes (steps, issues, positions and arguments), and identify which of them contain the keyword "odour" in its description. In the example, odour appears previous to the development of sludge-line only once, in the SCREENING-EQUIPMENT issue, where one of the positions (comminutor and grinders) was argued to avoid odours, flies and unsightliness. This position, although considered, was finally rejected. In this manner, the designers of the sludge line have easily found the role of this factor during the overall design of the WWTP case study.

4.4. Automatic evaluation of design alternatives

As mentioned in Section 2, an objective can be used to evaluate the adequacy of a design alternative. To do this, KBDS checks whether the values of the variables in a design alternative satisfy the constraints specified in a given objective.

In order to show this capability, two different design alternatives corresponding to the last flowsheet in the WWTP design case study (FINAL-WWTP) have been evaluated with respect to the first objective of the design, that is, to meet the water quality legal requirements fixed by the European regulation. This objective is reflected in the design objectives space as OBJ1 (see Table 2), but its evaluation by the computer is not possible as it is written in natural language. For this reason the objective had been refined into OBJ2 which contains the legal criteria expressed as constraints. The result of evaluating OBJ2 against the first operational alternative of FINAL-WWTP



IBIS-Report Date: 13/6/1997 Time: 16:37 Project: WWTP-DESIGN Generated By: RENE @ STOW

For the problem Issue: What oxygen transfer & mixing equipment to consider? Raised by Ignasi in reference to the flowsheet S-TREAT1, the solution selected was:

- Position: To consider mechanical surface aerator as oxygen transfer & mixing equipment, (suggested by Ignasi) because
    - ◊ Argument: high capacity input per unit volume (as argued by Ignasi)
    - ◊ Argument: low capital cost (as argued by Rene)
    - ◊ Argument: ideal for complete mix bioreactors (as argued by Manel)
    - ◊ Argument: tank design flexibility (as argued by Ignasi)

The following alternative solutions to the problem were also considered but were not selected:

- Position: To consider submerged turbines as oxygen transfer & mixing equipment, (suggested by Ignasi). This was not selected even though it is true that
    - ◊ Argument: no icing or splash (as argued by Rene)
    - ◊ Argument: good mixing (as argued by Ignasi)
    - ◊ Argument: good operational flexibility (as argued by Manel)
    - ◊ Argument: high capacity input per unit volume (as argued by Ignasi)
- Position: To consider horizontal rotors as oxygen transfer & mixing equipment, (suggested by Rene). This was not selected because it was not the case that
    - ◊ Argument: ideal for oxidation ditches (as argued by Ignasi)

  This was not selected even though it is true that
    - ◊ Argument: good maintenance accesability (as argued by Rene)
    - ◊ Argument: moderate initial cost (as argued by Rene)
- Position: To consider diffused air as oxygen transfer & mixing equipment, (suggested by Manel). This was not selected because it was not the case that
    - ◊ Argument: ideal for a plug flow bioreactor (as argued by Ignasi)

  This was not selected even though it is true that
    - ◊ Argument: good operational flexibility (as argued by Manel)

Fig. 9. Report describing the issue *Oxygen transfer and mixing requirements*?

can be seen in Fig. 8, and shows how this alternative meets the legal environmental quality expressed as two constraints in the objective, the first referring to suspended solids in the outflow stream (SS OUTFLOW-1 $<$ 35 : True), and the second referring to biodegradable organic matter at the outflow of the plant (BO DOUTFLOW-1 $<$ 25 : True). Similarly, the result of evaluating OBJ2 against the second operational alternative of FINAL-WWTP is also successful.

Referring back to Table 2, OBJ2 is refined into OBJ3, which contains additional legal criteria concerning nitrogen removal. The evaluation of any of the two operational alternatives of FINAL-WWTP with respect to OBJ3 (TKN OUTFLOW $<$ 10 mg/l, and P OUTFLOW $<$ 1 mg/l) would show that the plant is not able to meet this new constraint, which reflects the fact that the design of the WWTP case study does not contemplate the possibility of nutrient removal.

4.5. Modification of design objectives

The automatic evaluation of alternatives not only allows the designer to have instant feedback on the consequences of the modifications to the WWTP, but also can be used to verify if a design alternative is still valid after any of the constraints or specifications is modified or a new one is added. So if and when European regulation becomes stricter concerning the level of discharge of organic matter (e.g. from 25 to 15 BOD mg/l), the designer would only have to evolve the original objective into a new one including this new legal restriction. Then, a new evaluation of the objective against any design alternative could confirm if the alternative is still valid or if it would be necessary to change the FINAL-WWTP design.

In fact, KBDS can perform this check for all design alternatives in the design history and identify where the modified objective would affect a previous decision (i.e. would alter the ranking order of the positions). This would indicate the exact point(s) in the design where the designer would have to backtrack and start redesigning portions of the plant.

4.6. Re-use of design records

The topic of upgrading existing WWTPs is particularly important at this time because of the large number of existing facilities and the increasingly stringent discharge requirements imposed on them [24]. A clear example can be found in the retrofit of many WWTPs built during the eighties, which must now meet the European regulations on nutrient removal. This would be the case of the WWTP design case study shown in the paper. A suitable retrofit of this plant could easily re-use most of the units that have already been designed. A similar support for re-use can be applied when designing a similar plant.

KBDS can support re-use by evaluating the original design records with respect to a new set of objectives (embodying the goals of the retrofit or the new plant). Those parts of the original design that do not comply with the new objectives must be redesigned. Just as important, KBDS will increase the confidence of the designer in the parts to be re-used because of the added awareness on their original intent and rationale.

4.7. Automatic report generation

KBDS is able to generate reports automatically when a text-based description is associated to each node in the design rationale network. These reports describe the deliberation over a particular decision, e.g. the design rationale for the evolution of one design alternative to another. Fig. 9 presents a report describing the deliberation over the issue 17: *Oxygen transfer and mixing requirements?*

This report shows the four proposed positions for the issue, the selected solution, and the reasons for its choice. It also indicates when a position was rejected even though it had supporting arguments. Note that the name of the designer who has suggested a position or an argument appears in brackets.

There is a second type of report in KBDS (not shown because of the length of the generated document, e.g. around 50 pages for the project presented in this paper). It lists the deliberations that took place during the evolution of a design through several design alternatives (between two user-selected points in time). A system as KBDS has the potential to generate any kind of report based on the information recorded by the design team while the design process was being carried out.

4.8. Annotation of the design process

The representation of the design process recorded within KBDS has been extended enabling a variety of documents (text-based documents and figures) to be recorded as annotations. This allows a fuller representation of the design process and rationale, and eases the understanding of the argumentation upon which decisions are based.

This concept was used in the WWTP case study, for example, by annotating some of the equipment with their calculation procedures and results.

4.9. Indexing and search of the design records revisited

As discussed in Section 3.5, KBDS can extract keywords from the textual information associated to a node. However, this method has the limitation of requiring an initial user-constructed dictionary. The approach above entails the following disadvantages: the risk of associating incomplete and erroneous information and the fact that, since the information is extracted locally from each node, it is context-independent, i.e. it results in a flat keyword structure. It would be preferable to have the keywords organised in a hierarchy. In short, the size and complexity of the task is such that it would be convenient to automate, at least partially, the identification and organisation of keywords. It turns out that it is possible to extract some keywords referring to structure by parsing the history of the evolution of the design alternatives and the internal structure of each of these alternatives. For this case study the resulting hierarchy of nodes would look like the one presented in Table 6. A similar keyword hierarchy can be obtained based on the streams of the WWTP rather than on its units.

Note that, as would be expected, the hierarchy shown in Table 6 replicates part of the structure hierarchy from Table 5.

The above example shows that it is possible to increase the role of a support system during the design process from a repository of historical information to a system that extracts and makes inference (in this case an organisation or classification task) to produce new knowledge or make explicit previously implicit information. In particular, the keywords in the boxed text were extracted from the structure of the WWTP and were related following the refinement of the plant from an initial abstract block, STAGE0, to the final detailed flowsheet, FINAL-WWTP. Thus, the link between the keywords in the boxed text is a “part-of” relationship.

Even more sophisticated relationships between keywords could be detected in the future because KBDS can capture the evolution of the description of a design artefact over time. For example, a block at the initial stages of design may have an associated textual document discussing its possible desired properties. When this block is refined into a series of unit operations, the concepts in the associated document may be considered to have evolved into the various units, e.g. from text, to goal, then argument and finally a component in the WWTP. In other words, KBDS supports the incremental formalisation of design data, as proposed and developed by Refs. [25,26].

5. Conclusions

The paper describes a case study of the plausible application of a Design Support System to WWTP design. A list of advantages has been presented in detail which includes: the ranking of different options; the relative influence of arguments during decision-making; the use of keywords during search of design records; the automatic evaluation of different alternatives with respect to the design objectives; the verification of these alternatives after any modification; the re-use of the design records when upgrading or designing a new plant; and the automatic generation of documentation.

These features improve and simplify the tasks of designers when designing and retrofitting a WWTP and,

Table 6
Derivation of a hierarchy of keywords based on the structure of the WWTP and its evolution through the design process

- Wwtp-plant
  - Water-line
    - Pretreatment
      - Screening
        - Bar-screens
      - Grit-removal
        - Aerated-grit-chamber
      - Flow-measurement
        - Flume-metre
    - Primary-treatment
      - Primary-settler
    - Secondary-treatment
      - Suspended-growth
        - Complete-mix-bioreactor
        - Secondary-settler
        - Sludge-separator
  - Sludge-line
    - Thickening
      - Primary-sludge-degritting
      - Primary-sludge-thickening
        - Gravity-thickening
      - Secondary-sludge-thickening
        - DAF
      - Mix-sludge
        - Mix-thickening-sidestreams
  - Stabilisation
    - Anaerobic-digestor
  - Dewatering
    - Pressure-filter-presses
  - Mix-sidestreams

when they have to design a similar plant, re-using most of the information recorded in the design support system. The design process is improved as a result, i.e. becomes one with fewer, shorter and cheaper design cycles.

Some of these advantages have already been observed in an industrial context. Unfortunately, detailed results are proprietary. However, we believe that the results presented allow the reader to envisage the future impact of design support systems and the suitability of KBDS. In summary, KBDS has been shown to be a suitable tool to assist the WWTP design process.

Acknowledgements

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