Decision support system for optimizing the configuration and operation of a multi-process waste water treatment plant of an oil & gas refinery

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Abstract:

Increasing the efficiency of an industrial wastewater treatment plant facing complex and variable wastewater composition is a challenging objective. The challenge comes from the need of using multiple specialized processes that effectively deal with a certain stage of the wastewater treatment at low cost.

This is the objective of the Integroil project: to optimize the operation of a wastewater treatment plant by means of developing a decision support system (DSS) and to test it into a pilot plant used for produced water treatment of the oil&gas sector (upstream and downstream scenario). The objective of the DSS is to assess the possible configurations of the plant given the wastewater quality parameters and the characteristics of each process and to select the best configuration (active processes) of the plant that provides the output water requirements in the most sustainable and economic way.

The challenge of such a project lies in a number of factors: the complex composition of the water to be treated in the refinery, the limitations imposed by the hydrocarbon rich environment in choosing effective water treatment processes, and not least, the efficient usage of these processes for maintaining the operation costs at a low level.

The Integroil project has designed and constructed a pilot plant that uses five different processes: dissolved air flotation (DAF), ceramic ultrafiltration (UF), advanced oxidation (AOP), catalytic wet air oxidation (CWAO), and reverse osmosis (RO). These processes are integrated into a centralized control architecture and a DSS which adapts the configuration of the plant according to the changes in the influent wastewater characteristics and the three selectable effluent water requirements, according to their application: irrigation, extraction and ocean discharge.

1 Introduction

The H2020 Integroil project aims at developing and demonstrating a robust but flexible integrated solution for treating water flows with variable compositions up to be reused. This new solution is comprised by innovative treatment technologies effectively arranged and optimized through a novel Decision Support System (DSS), capable of producing fit-for-use reclaimed water, increasing the overall sustainability and competitiveness of the Oil&Gas (O&G) sector [1][2].The technologies which comprise this solutioninclude dissolved air flotation (DAF), ceramic ultrafiltration (UF) [3], advanced oxidation (AOP) [4], catalytic wet air oxidation (CWAO) [5] and reverse osmosis (RO) [6] and will be combined in order to deal with oil refinery.

These processes were developed and optimised individually at pilot scale. The pilot plant will be demonstrated in two operational sites representing the upstream and downstream scenario. Their integration into a centrally controlled pilot plant that is managed by a decision support system (DSS), further optimizes the operation on a global perspective. The DSS coordinates the configuration and operation of all the processes in an automatic manner, complying with the water quality requirements while minimising the costs of operation.

DSS have been implemented before having a focus on water management at a region or building level - where different consumption patterns can be observed, as presented in [7] and [8]. A DSS feature for the automatic reconfiguration of the water plant, to the authors knowledge, is not a common feature to be found.

The pilot plant was conceived as a modular architecture, as close as possible to a “plug & play” concept, applying minimal modifications in the hardware structure and programming settings. However, it must be mentioned that due to the safety requirements, hardware flexibility limitations and programming constraints typical from industrial automation, this “plug & play” concept can be implemented up to a certain limit, requiring some degree of hardware modifications and pipe fitting and a period of software integration of different processes.

The development of the communication and control architecture of the plant has three principal directives:

- Modularity: each process was built by a different technology developer that has extensive knowledge of the process; using a distinct PLC for each process gave the partners the ability to develop the best control of their process.
- Integration: as each of the process uses the same type of PLC, the integration stage was easier – all the controls are of the same type which facilitates the implementation of the communication between the PLCs.
- Centralized control: a central PLC was used to implement the DSS that governs the configuration and operation of the entire plant.

These directives assure the ease of integration of the different processes and the global optimization of the pilot plant operation while producing the required type of water.

The following sections will detail the types of water required from the pilot plant treatment (section 2), the plant description (section 3) modeling of the configuration algorithm of the DSS (section 4), simulations and operation results (section 5) and conclusions (section 6).

2 Water quality and its associated challenges

The O&G industry is considered one of the eight most water-intensive industries due to the high volumes of water that are required for oil extraction and refining, and the subsequent amount of wastewater that is generated [1] [2]. Therefore, it mainly deals with two water treatment scenarios: upstream, where water and crude oil or natural gas from the reservoir are extracted (produced water) and downstream, which corresponds to the water involved in the process of oil refining.

Tin the case of produced water, its main characteristic is its complexity as it is often highly saline (total dissolved solids (TDS): 100 mg/L- 400,000 mg/L) and it contains hydrocarbons (benzene, toluene, ethylbenzene and xylenes (BTEX), naphthalene, phenantherene, dibenzothiophene (NPD), polyaromatic hydrocarbons (PAHs) and phenols, among others) and toxic chemicals. Downstream scenario involve complex and variable industrial wastewater.

Although conceptually the problems look similar between upstream and downstream scenarios, with a combination of high suspended solids, oil and grease, dissolved organic matter and even high nitrogen concentration, the way of addressing the treatment of refinery wastewater has been historically different than produced water, by systems based on biological treatment with some pre-treatments and post-treatments, as compared to the physico-chemical treatments conventionally deployed in the latter. Furthermore, in both cases conventional wastewater treatment facilities are not fully reliable and have not been designed as integrated solutions for water reuse.

Process water and refinery wastewater has been deeply characterised in order to assess the technologies in representative scenarios in both cases. In addition to this, various final uses of the reclaimed water produced have been defined for each scenario, involving different requirements in terms of quality:

- Downstream scenario: firefighting water, cooling water and demineralized water
- Downstream upstream scenario: irrigation water, extraction reuse water and ocean discharge water

3 Pilot plant description

A 1,5 m^3/h containerised pilot plant consisting on DAF, UF, AOP, CWAO and RO has been designed constructed and is currently under operation. The pilot plant has been designed in such a way that these technologies can be combined in different manners (incl. by-passed), enabling the testing of numerous configurations, hence providing a high degree of flexibility. It is fully automatized, autonomous and equipped with on line analysers and has a central PLC capable of controlling and optimizing all the process globally, based on the DSS results. Additional off line analysis are carried out as required.

The DAF system (1,5m^3/h capacity), developed by Acciona Agua, consists of two coagulation/flocculation chambers, attached to the so-called floater, and a saturator where air is dissolved into a water recirculation stream by means of pressure injection.

The UF system (1,5m^3/h capacity), developed by Likuid, consists of a L6101 ceramic module (20 nm cut off, 19 channels and 15 m^2 of surface area), works at constant flow, in crossflow mode and is able to conduct backwashes and cleaning operations as needed. In case of the downstream scenario, the UF membrane is located inside a biological reactor, acting as a membrane bioreactor (MBR).

The CWAO system (1m^3/h capacity), developed by Aplicat, consists of a catalytic reactor, where an adsorbent is placed and works at constant flow and room temperature and pressure. When the catalyst is saturated, the regeneration process takes place and an analogous second reactor is put into operation, to enable the continuous operation.

The AOP system (1m^3/h capacity), developed by URV, consists of the addition of ozone and sodium hydroxide, enabling a continuous operation at constant flow. A gas-liquid separator and a subsequent mixed catalytic-thermic trap ensure the removal of any remaining ozone.

The RO system (0,9m^3/h capacity), designed by Acciona Agua, consists of a three 4” elements arranged in a pressure vessel, corresponding to a one-stage system. It is equipped with a security 5 µm cartridge filter and all the required ancillary equipment to enable cleaning labors as required.

4 Modelling

The two main objectives of the DSS are i) to select the most convenient water treatment scheme based on the influent water quality and the effluent requirements (i.e. to select and to combine which technologies should be active); ii) to optimise the operational conditions of each technology in order to decrease the chemical and energy consumption as well as to maximise the water yield.

For the former objective, the DSS uses a reconfiguration algorithm to generate the best (optimal) configuration of the pilot plant that complies with the output water requirements. This algorithm, described in the following sub-section, was developed and validated in a series of simulation scenarios using Matlab and then implemented into the general PLC of the pilot plant.

4.1 Reconfiguration algorithm description

In essence, the reconfiguration algorithm is using a "greedy" technique for choosing, at each step, the best possible candidate for minimizing the overall cost. The cost in this case is defined as a sum of monetizable costs (energy and chemical reagents) and a set of virtual costs used for describing the availability of each process and the effect the influent water can have on the respective process. This does not assure a global optimal solution but the selection of the optimal process at each step of the process selection – hence the “greedy” nature of the algorithm.

The algorithm also uses different sources of information, as seen in Figure 1:

- It relies on memory stored parameters that characterize the processes (“info reject”, “info input_limit”, “info coeff_start”, “info coste_oper”, as described below)
- These parameters are being initialized with values obtained through previous laboratory experiments and knowledge of the process – provided by each technology developer (“Process identification” from Figure 1).
- Online measurements that are obtained during the operation of the pilot plant and used to tune the stored parameters (“Measurements” from Figure 1). Therefore, the algorithm can be improved based on the system performance.

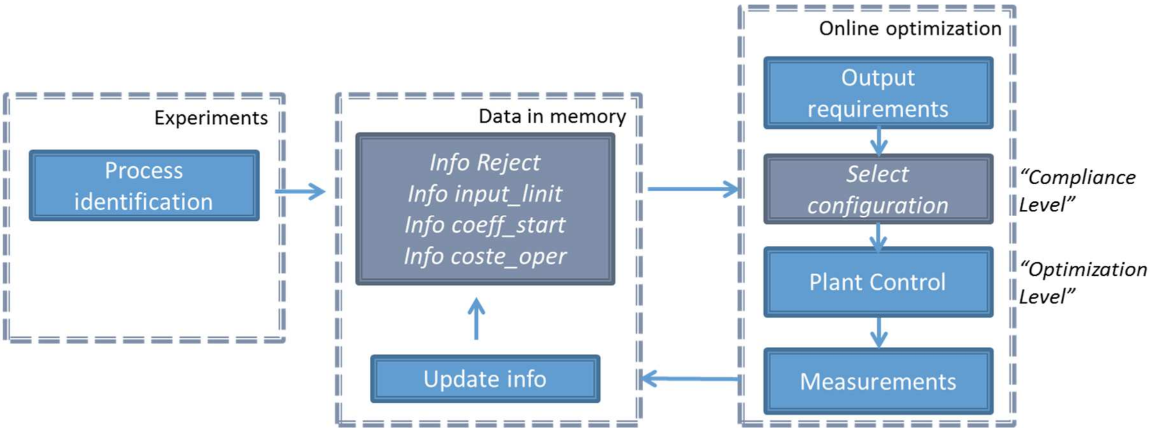


Figure 1 Decision Support System architecture

The algorithm relies on the data stored in the memory in the form of four tables:

- Reject – It is a table which contains 5 columns (one for each process) and 3 rows (one for each water quality parameter considered. As an example, three water quality parameters have been selected initially: turbidity, total organic carbon (TOC) and conductivity). The values in the table represent the maximum rejection capabilities of each process regarding a certain water quality parameter of the inffluent water. For instance, RO will reject 99% of the salts and therefore the measurable conductivity will be virtually eliminated; on the other hand, the DAF will have no effect / no elimination of conductivity from the influent water.

- Input_limit – It is a table that stores the acceptable value for each of the quality parameters for entering a certain process; for example, the DAF has no input_limit for turbidity; however, the RO process is sensitive to turbidity and oil so it has a very low level of accepted input_limit.

- Coef_start – It is a vector where each process has an associated startup (virtual) cost coefficient. This "cost" represents the penalty of using the process close or above the defined input water quality limit. It is defined as a virtual cost as it does not represent a clear monetary value but an effect in time.

- Cost_oper – It is a vector where each process has an associated operating cost coefficient. This cost could approximate a monetary unit as it uses averaged historical consumption values.

For making a decision between which processes to activate, the algorithm requires representing the efficiency of different processes in a numerical form in order to be comparable. As the current algorithm considers many different characteristics of the process that have different physical meaning (energy consumption, rejection capability, process limits), defining a single numerical value ("virtual" cost) that includes all these elements reduces the physical meaning of the numerical value.

Therefore, the cost that the algorithm uses is not a monetary unit (it does not only count the energy and chemical consumption) but is a function that maps different operation conditions of a process to a value that can be further compared to the "virtual cost" of using a different process instead.

4.2 Reconfiguration algorithm operation

The algorithm starts with an empty list of processes with the objective to find the best sequence of processes that connected, would provide the required quality of the effluent water at the plant's output, at minimal cost.

At each step it searches and compares, from the available remaining processes, which process is "cheaper" to select as the next process in the sequence/configuration of the plant.

The algorithm repeats this process until the theoretical quality of the effluent water is obtained or all the processes have been used, as seen in Figure 2. In the phase of running the algorithm, the parameters defined in the previously mentioned tables are being used. Once the optimal configuration of the plant has been obtained, the valves are being actuated in order to implement the desired treatment scheme configuration.

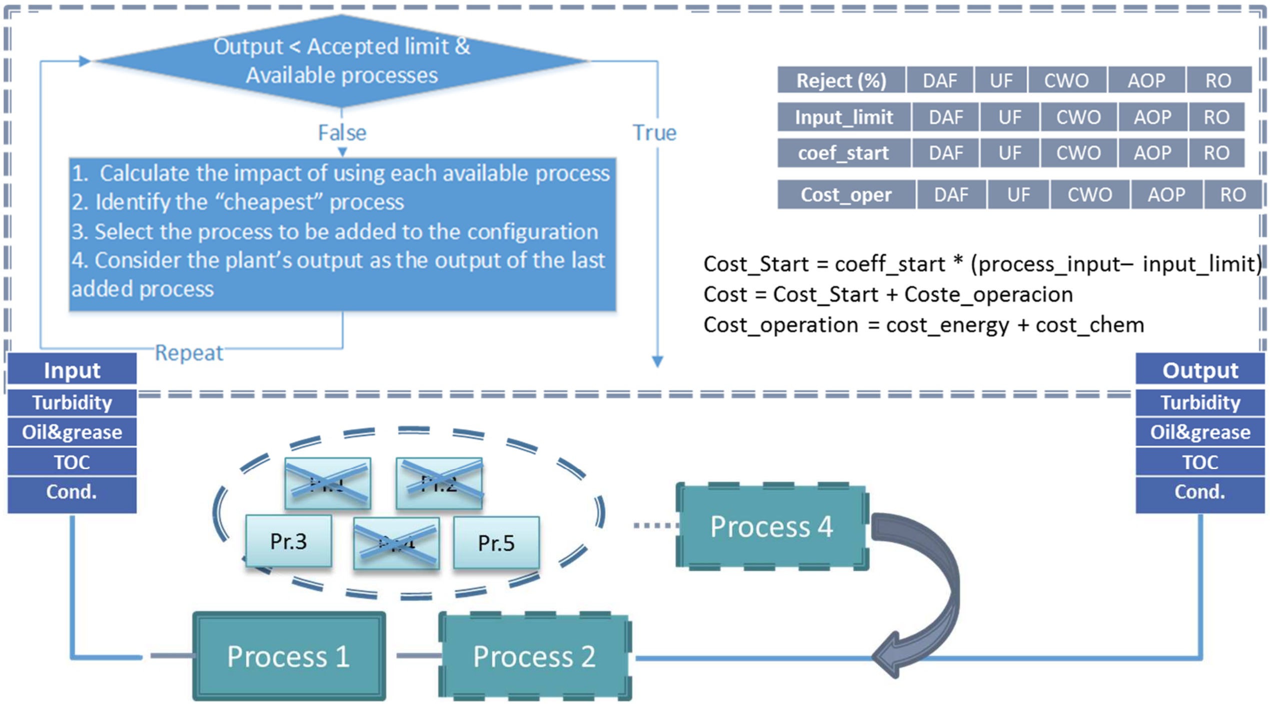


Figure 2 Decision Support System architecture

As seen in the above figure, the algorithm generates the configuration of the plant – identifying the necessary processes and the sequence (i.e. which process to go first, which to go second, etc.).

Adding new processes to the plant will imply extending the defined tables by an additional column where the characteristics of the new process (reject, input limits, coef_start, coef_oper) will be filled in. The algorithm will continue working with the same sequence, without any change; the difference comes from the fact that when adding a new process, the algorithm will be able to choose between more processes at each step. There is no limit on the number of process the algorithm can handle – is a matter of adding additional columns to the tables.

In addition to this, further key quality parameters can be added to the algorithm, in order to have a more accurate characterisation and selection when increasing the number of available technologies.

5 Simulations and results

The development of the DSS algorithm included various steps: design, implementation, and validation in the Matlab environment and the implementation and test in the real time PLC.The following sections will present the results through all these steps.

5.1 Simulations

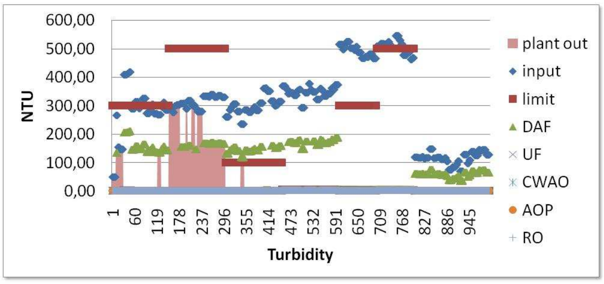
For validating the algorithm, it has been implemented in Matlab. The parameters for the necessary tables have been initialized with previously obtained data from each process developer.

The sequence has been tested with six different output water requirements based on its final application, defined in section 2. This represents the output requirements for the algorithm to comply with.

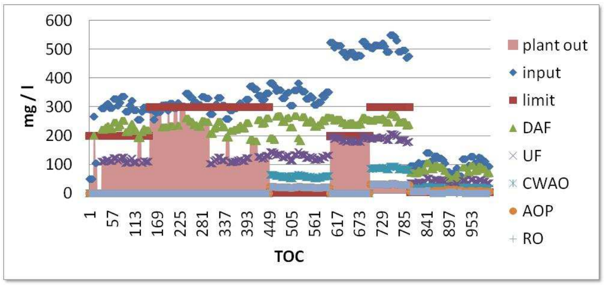
In addition, the algorithm has been tested with different input water qualities in order to evaluate its performance for different operational scenarios. An input water sequence has been generated having a variable characteristic concerning the three values: turbidity, total organic carbon and conductivity.

Figure 3 presents the simulation results obtained applying the DSS configuration algorithm. Figure 3d) represents the pilot plant's configuration: when a process is active, its corresponding colour is activated.

Depending on the input water quality, the algorithm selects which processes to active in order to comply with the required quality of the output water. Initially, DAF and UF are active, at 185 min UF is deactivated, at 325 min activated again and at 468 min all the five processes are activated (DAF, UF, CWAO, AOP, RO). Figure 3a), 3b) and 3c) represent each of the three main water parameters (turbidity, total organic carbon and conductivity, respectively) at the outlet of each process, as well as the inlet water (dark blue symbols) and the plant's output water (pale pink symbols). Additionally, the required output water quality that the algorithm must assure that is met after the proposed configuration, is marked in red. For example, in Figure 3b) initially TOC effluent content equals to the UF permeate value, since the influent water is only treated by DAF and UF. When all the processes are active, the TOC content is further decreased, being the RO permeate TOC content equal to the plant effluent value displayed (RO is the last treatment process). As can be seen, the DSS is capable of defining a treatment scheme whose final water quality fulfils the requirements, since they are always below the limit set.



a)



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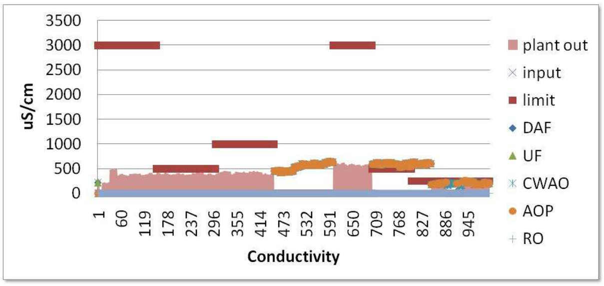
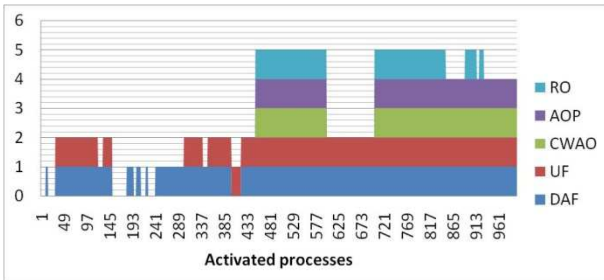


c)



d)

Figure 3a) (top left hand side) Simulated turbidity effluent values of each process evolution along time; 3b) (top right hand side) Simulated TOC effluent values of each process evolution along time; 3c) (bottom right hand side) Conductivity effluent values of each process evolution along time; 3d) (bottom right hand side) Active processes evolution along time

5.2 Operation results

A visualization of the real time operation of the pilot plant governed by the central PLC running the DSS can be seen in Figure 4. The operation scenario from Figure 4 shows the real time configuration of the plant (running processes) during various input water characteristics. As can be seen, processes are activated/deactivated based in the input water characteristics (Turbidity, TOC and conductivity) and output water requirements (irrigation, extraction and ocean discharge, etc.), providing a high degree of flexibility to the water treatment system.

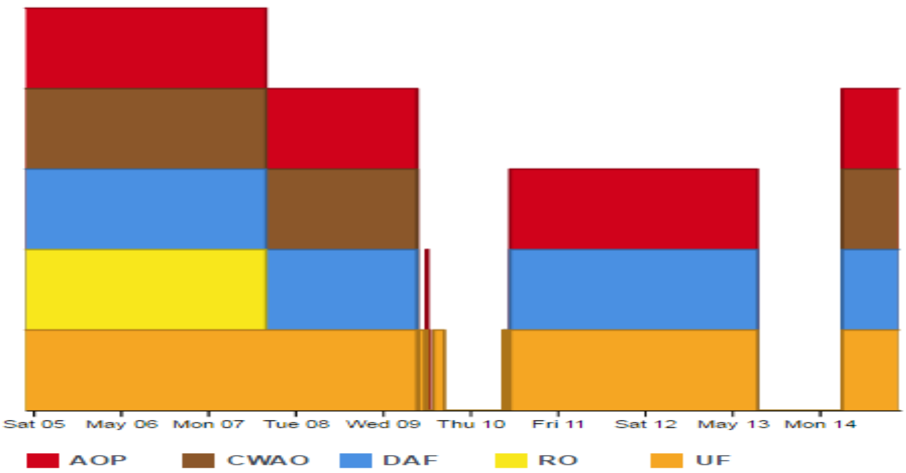


Figure 4. Online results of operating the plant

6 Conclusions

The paper presents a DSS algorithm that reconfigures the water treatment plant in order to comply with the requirements of predefined output water types, in order to obtain fit-for-use water in an economical way.

The algorithm presents a parameter initialization based on previous experience and data and the possibility of tuning these parameters based on historical operation scenarios where the new parameters values, that better estimate the process.

The proposed algorithm presents high flexibility in the case of augmenting the number of unitary processes conforming the plant once the physical modifications have been made: at the algorithm level, the required modifications imply adding a new column for each new process. Moreover, further quality parameters can be taken into account if needed.

The algorithm is prepared for treating different types of water under a wide range of scenarios, finding the configuration that is suitable for each scenario. Even though this DSS and treatment scheme is being tested at pilot scale for the Oil and Gas industry (both in the upstream and downstream scenarios), it is expected to be applicable in other industries which deal with highly variable and complex waters. Due to the DSS robustness, reliability, flexibility and user-friendliness it is expected to increase the efficiency of water treatment processes in industries (chemicals and energy reduction and water yield increase mainly), boosting industrial water reuse and thus, increasing their sustainability.

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