Diagnosis and optimization of WWTPs using the PWM library: full-scale experiences
T. Fernández-Arévalo, I. Lizarralde, M. Maiza, S. Beltrán, P. Grau and E. Ayesa

ABSTRACT
Given the shift in perception of wastewater treatment plants as water resource recovery facilities, conventional mathematical models need to be updated. The resource recovery perspective should be applied to new processes, technologies and plant layouts. The number and level of models proposed to date give an overview of the complexity of the new plant configurations and provides a wide range of possibilities and process combinations in order to construct plant layouts. This diversity makes the development of standard, modular and flexible tools and model libraries that allow the incorporation of new processes and components in a straightforward way a necessity. In this regard, the plant-wide modelling (PWM) library is a complete model library that includes conventional and advanced technologies and that allows economic and energetic analyses to be carried out in a holistic way. This paper shows the fundamentals of this PWM library that is built upon the above-mentioned premises and the application of the PWM library in three different full-scale case studies.

Key words | aeration, full-scale simulations, global energy analysis, phosphorus management, PWM library

INTRODUCTION

Wastewater treatment (WWT) modelling originated in the field of academia, developed mainly by academics interested in research. At the end of the last century, it became established as a tool for research. Proof of this is the linear rise in the last 25 years of publications related to activated sludge modelling (adapted from Gujer 2006; Rieger et al. 2010), which has become a suitable tool for the optimization of WWT processes, the design of new wastewater treatment plants (WWTPs) and the upgrading of existing ones. Depending on these application areas (academia, research or consultancy), the perception of the usefulness of a model may differ. For the fields of applied research and consulting, which are the areas where plant optimizations and diagnostics are framed, a model has to be an abstract representation of the real system to support decision-making. Thus, the value of a model should depend on its usefulness in supporting decision-making (Daigger 2011).

While a few years ago this decision-making was focused solely on ensuring effluent quality and minimizing energy consumption, the scarcity of natural resources and concern about climate change have led to an increasing awareness of the importance of resource recovery, energy minimization and environmental impact assessment. To address this change, the water sector is developing new and innovative treatment technologies, such as resource recovery systems, partial nitritation/Anammox technologies for nitrogen (N) treatment and sludge pre-treatment processes, among others. Combining these innovative processes with traditional technologies has led to new plant configurations that are based on offering sustainable solutions for obtaining effluent quality while, at the same time, optimizing the recovery of valuable by products and energy. This awareness, in conjunction with the changes in regulation, community and national standards, has led many WWTPs have to be updated and retrofitted.

However, prior to any full-scale implementation, a preliminary assessment is recommended in order to analyse the economic feasibility of the proposed changes, as well as the effect of incorporating technologies in the whole...
plant. In this context, model-based explorations are a very useful tool to quickly assess WWTP upgrades.

Mathematical modelling has been evolving to keep up the new innovations in technology. For example, models have been developed for, among many things, describing chemical and physico-chemical phenomena (Batstone et al. 2012; Flores-Alsina et al. 2015; Kazadi Mbamba et al. 2015a, 2015b; Lizarralde et al. 2015), for estimating operational costs (Simba 1999; Copp 2002; Rieger et al. 2006; Descoïns et al. 2012; Aymérich et al. 2015; Fernández-Arévalo et al. 2015), for describing the heat transfer in unit-processes (Gillot & Vanrolleghem 2003; Makinia et al. 2005; Gómez et al. 2007; de Gracia et al. 2009; Fernández-Arévalo et al. 2014; Corbalá-Robles et al. 2016) and for predicting the production of greenhouse gases emissions (Ni et al. 2011, 2013, 2014; Guo et al. 2012; Guo & Vanrolleghem 2014; Mampaey et al. 2013; Snip et al. 2014). Due to the complexity of the new configurations and processes where there are recirculations and interrelations among the units, it is necessary to consider a plant-wide perspective in order to establish an optimum solution for the design or operation of the entire plant (Grau et al. 2007; Jeppsson et al. 2007; Nopens et al. 2009). In addressing this need, different models or methodologies have also been developed in order to describe the whole plant, considering both, the water line and the sludge line (Ekama et al. 2006; Grau et al. 2007; Jeppsson et al. 2007; Barat et al. 2013; Ikumi et al. 2014a, 2015; Flores-Alsina et al. 2015).

The knowledge gained about process modelling is extensive. Proof of this is the number of works mentioned. However, the bottleneck appears when all or many of these models are to be used together; that is, when knowledge has to be integrated in a compatible way. Each model has its components and its structure, and the combination of these is not always easy and immediate. The tool proposal in this paper is the plant-wide modelling methodology (PWM). This methodology was first proposed in 2006, and since then it has undergone continual improvement, adding features to keep it up to date (de Gracia et al. 2006, 2009; Grau et al. 2007; Fernández-Arévalo et al. 2014, 2015; Lizarralde et al. 2015). The methodology allows adapting existing models, ensuring the continuity of mass and energy in each transformation in order to obtain compatible models and transformations. The methodology's bases have made it possible to develop and standardize a flexible and expandable model repository or model library that can be adapted to any plant configuration and any set of current or future process transformations. This model library should include models that are complex enough to describe biological and abiotic phenomena in as detailed a manner as required, but there also need to have elements that translate this complexity into variables that can be used and understood by engineers and plant operators. This paper aims to show, using the example of three full-scale plants, the necessity and usefulness of advanced modelling methodologies and libraries to jointly simulate the needs identified in real plants by plant operators and by the water sector authorities in general.

PLANT-WIDE MODELLING (PWM) LIBRARY

The plant-wide modelling library (Figure 1) has been developed in accordance with the PWM methodology proposed by Grau et al. (2007), Fernández-Arévalo et al. (2014) and Lizarralde et al. (2015). Although the methodology was originally conceived for the construction of plant-wide models (Grau et al. 2007), its hypotheses and principles made it very suitable for developing models with the requirements mentioned in the introduction. From the initial foundations, further developments were made for thermal energy calculations (Fernández-Arévalo et al. 2014), for chemical and physico-chemical processes incorporation (Lizarralde et al. 2015) and for cost estimation (Fernández-Arévalo et al. 2015).

The new model library compiles information arranged by the various aspects that need to be considered in the construction of the model, such that the modeller can select the ones that are of interest to the case under study, by following these three steps:

1. Select the categories or transformation lists. The library contains different categories that compile components and transformations into different packages depending on the biological, chemical and physico-chemical transformations to be described.
2. Select the unit-process models (e.g. continuous stirred tank reactors (CSTRs), primary or secondary settlers, solid separation systems, etc.), where the mass and heat transports are defined depending on the phases considered in the unit processes under study.
3. Select the actuators, specific energy ratios and dosage cost models required in the cost estimation.

Once the categories, the unit-processes and the cost models have been selected, the model is constituted and ready for use.
Categories or transformation list selection

The selection of category has to ensure the right description of the biochemical, chemical and physico-chemical transformations that may take place throughout the plant. The first important feature of the library is that it is composed of a list of compatible transformations, so with a unique standard model it is possible to simulate the plant as a whole. The unification of this set of transformations permits a unique component vector to be defined for the whole plant, without the need to develop specific transformers for interfacing unit-process models. The use of a common list allows a more realistic component characterization, with constant elemental mass fractions and constant stoichiometric values throughout the plant, thus avoiding some of the uncertainty caused by the interfaces (Grau et al. 2007). Accurately defining the stoichiometry ensures the elemental mass (in terms of C, N, O, H, P or other elements) and charge continuity in all these transformations (Grau et al. 2007), while defining the enthalpies of formation of each component allows the reaction heat of each transformation to be estimated (Fernández-Arévalo et al. 2014). The second important feature of the library is that it is composed of existing models, all of which have been adapted or re-written for compatibility. Transformations describing biological processes in all categories are based on ASM1/2d (Henze et al. 2000) for chemical oxygen demand (COD), N and phosphorus (P) removal; ADM1 (Batstone et al. 2002) for anaerobic COD biodegradation and in the works of Hellinga et al. (1999) and Hao et al. (2002a, 2002b) for the Anammox and two step N removal. The chemical and physico-chemical transformations were selected based on work by Ikumi et al. (2009) and then incorporated according to the methodology and kinetic expressions presented in Lizarralde et al. (2015). Thus, the organized structure that the methodology presents enables the straightforward development of categories, allowing the library to be continuously updated.
Unit process models

The library contains a comprehensive set of unit-process models. Each unit process model (UPM) incorporates the mathematical description of the mass transport and the heat balance for each phase (liquid, gaseous, solid) and the transformations designated in the category by following a matrix structure (Fernández-Arévalo et al. 2014). The main feature of these models is that they are compatible and standard. The models are defined and developed in such a way that they can be used for any existing or future category, and they are defined based on the phases contained (number and type), and system inputs and outputs. In this way, it is possible to use the same model to describe thermal hydrolysis or aerobic digestion processes.

Cost models

Finally, the library includes a set of actuators, specific energy ratios and dosage cost models for a detailed estimation of the costs of each element (Fernández-Arévalo et al. 2015). All actuator models are developed based on engineering expressions instead of directly using cost curves or fixed values. This creates a connection between all elements of the library, since the actuator expressions depend on operational variables (flow rates, heats of reaction, solids concentration, etc.) that are estimated in the UPM and UPMs depend on categories. The goal is to have more accurate models in which the oversimplifications and the low degree of standardization of some expressions are avoided. The models are standardized, so they can be used interchangeably in any category. The standardization of the models has been sought to keep future model adaptations from being needed when new components are incorporated, and to keep in line with the standardization philosophy of the plant-wide modelling methodology.

### DIAGONOSING AND OPTIMIZING WWTPS USING THE PWM LIBRARY

In applied research simulation studies in particular, the response time must be short. Immediate answers are expected, with proven models. For these types of studies, the key to running a correct simulation study is to follow simulation guidelines that are based on high methodological rigor and appropriate modelling tools. With regard to modelling tools, the complexity of the models used and their degree of detail has always been a topic of discussion. But experience has shown that the solution is not to use complex models in all cases in order to obtain accurate results, nor is it to shorten the time and effort that go into calibration and simulation. Instead, the solution is to use the particular model that is adapted to the needs of the case study.

The three full-scale plants selected to illustrate examples of model-based diagnosis and optimization are located in Spain. All these plant layouts have been constructed and implemented in the WEST simulation platform (www.mikebydhi.com), and the configuration details and main goals of each study are shown in Table 1.

In the examples presented below, the needs observed in the treated plants and demanded by plant operators and water authorities are shown.

#### Table 1 Specifications of the three WWTPs in the case study (D: denitrification; N: Nitrification; R: Regeneration)

<table>
<thead>
<tr>
<th>Plant load [pe]</th>
<th>Effluent requirements</th>
<th>Removal process</th>
<th>Water treatment train</th>
<th>Sludge treatment train</th>
<th>Brief description of the study</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Galindo WWTP</strong></td>
<td>COD &lt; 125 gCOD/m³</td>
<td>Bio C/N</td>
<td>Primary/RDN or DRDN conf./sec. clarifier</td>
<td>Thickener/dewatering/ incinerator</td>
<td>Global energy analysis</td>
</tr>
<tr>
<td><strong>Cartuja WWTP</strong></td>
<td>TSS &lt; 35 gSS/m³</td>
<td>Bio C + Chem. P</td>
<td>Primary/plug-flow activated sludge process</td>
<td>Thickener/dewatering/ incinerator</td>
<td>Detailed analysis of the aeration system</td>
</tr>
<tr>
<td><strong>Palma 1 &amp; 2 WWTPs</strong></td>
<td>TN &lt; 10 gN/m³</td>
<td>TP &lt; 2 gP/m³</td>
<td>Palma 1: Primary/DN or DNDN w precipitation</td>
<td>Thickener (sludge Palma 1&amp;2) /digestor/dewatering</td>
<td>Economic analysis of P removal/recovery alternatives</td>
</tr>
</tbody>
</table>
Galindo-Bilbao WWTP

The main aim of this model-based study was to carry out a comprehensive energy and operating cost analysis of Galindo-Bilbao WWTP. The study was divided into two parts. The first analysis consisted of an assessment of current operation, paying attention to the distribution of operational costs over one year of operation in order to identify the most significant operating expenses and the variability of each. This plant does not have units to recover compounds, but it has a control strategy composed of three complementary control loops: a cascade ammonia or NH₄-N controller to maintain the average concentration of NH₄-N in the effluent, a nitrate controller to optimize the use of the denitrification potential, and a final control loop to maintain the mixed liquor suspended solids (MLSS) concentration in the biological reactors or the MLSS concentration by automatic manipulation of the wastage rate (Ayesa et al. 2006). As the plant did not wish to make improvements, one of the clearest alternatives for minimizing operating costs was to explore via simulation the different alternatives for COD management throughout the entire plant, an analysis that is tackled in the second part of the study. The overall study helped with the operational decision-making, not only from the standpoint of ensuring the quality of the effluent, but also from a perspective of energy minimization.

Given the Galindo WWTP’s characteristics, the CN category was selected in order to reproduce the behaviour of the plant. This category gathers all components and transformations that describe dynamic aerobic and anoxic COD biodegradation and N removal. From the unit-process model library, a primary and secondary clarifier, 10 completely stirred open tank reactors, one buffer tank, two thickening units, a dewatering unit and two incineration units were selected. Finally, blower, pump, agitation engine, dosage costs and electricity conversion models were selected from the cost model list. Specifically, in this study, the elemental mass characterization of model components and the consideration of heat balances in all processes allowed for the rigorous calculation of heat exchanges. This had an important effect on the incineration process, as will be seen in the discussion about the results.

As an example that illustrates the potential of PWM simulations, Figure 2(a) shows the distribution of the most significant operational costs over a year of operation: aeration, pumping and dewatering electricity costs and polyelectrolyte and natural gas (NG) dosage costs. In this first analysis, fixed costs or costs which cannot be manipulated (main pumping, pre-treatment, scrapers, odour treatment, flotation, mixing and auxiliary services) have not been considered. Taking average values, the plant’s operating costs were divided as follows: 22% aeration, 7.5% pumping, 7% dewatering, 7.5% polyelectrolyte dosage, 6% NG fed into incineration and 50% other costs (fixed costs or costs which cannot be handled). As can be seen, aeration costs represent a small part of the overall costs. In the Galindo WWTP, this is a consequence of both the high treatment capacity of the plant which allows the use of more powerful and efficient blowers, and the use of advanced ammonium and nitrate controllers. In assessing the dynamic operating costs (Figure 2(a)), it can be seen that periods with higher operating costs correspond with considerable use of NG in incineration. The incineration process needs to maintain the combustion temperature (≈900°C) in order to properly remove the matter. In cases in which the dewatered sludge does not generate enough energy to achieve this temperature, NG is fed into it, which significantly increases overall operating costs. After a thorough analysis of the data, it was found that these variations correspond to periods of high rainfall. These

![Figure 2](https://iwaponline.com/wst/article-pdf/75/3/518/455300/wst075030518.pdf)
weather conditions diluted the concentrations of COD, NH₄-N and volatile suspended solids (VSS) and increased inert inorganic solids concentrations. Since the degree of dryness of dewatered sludge was kept constant throughout the year, a sludge with a lower VSS/TSS (volatile and total suspended solids) ratio was obtained in times of high rainfall. This situation produces a sludge with less biodegradable material and needs more NG in order to be incinerated. To reduce this NG consumption, the dehydration criterion had to be changed from constant dryness to a constant VSS concentration.

With this plant, a scenario analysis was carried out by assessing the operating cost for different primary clarifier TSS removal efficiencies (\( \eta_{TSS} \)) and MLSS concentrations, that is, different options for managing the COD in the plant in winter and summer. To simulate the \( \eta_{TSS} \) increase, a dosage of ferric chloride (FeCl₃) was added to the primary clarifier. The amount of added concentration was estimated based on the expression proposed by Tik et al. (2013) and the cost function is presented in Fernández-Arévalo (2016). The MLSS concentration, in turn, was modified by the automatic manipulation of the wastage rate (solids retention time variation). To interpret the results, regimen maps were used (Figure 2(b) and 2(c)), and in all cases the effluent quality requirements were guaranteed thanks to the control loops. Analysing the results shows that in both scenarios (winter or Figure 2(b) and summer or Figure 2(c)) operating costs are lower when the solids removal efficiency of the primary settling is increased, despite having to add FeCl₃. This occurs as a result of the sum of several factors: air requirements are lower, the secondary sludge pumping has higher operational costs, the needs for polyelectrolyte is lower for primary sludge than for secondary sludge, and the energy generated in the incineration process is greater, and thus a lower NG dosage is required. Regarding the effect of solids concentration in biological reactors, the smaller the SRT, the greater the operating costs. In this case, it can be explained as follows: the higher the solids concentration in the biological reactor, the higher the costs of aeration, but the lower the dosage (polyelectrolyte and NG) and pumping costs.

In the operation of a real plant it is difficult to control the \( \eta_{TSS} \), as it is dependent on the influent and rejected water composition, load and flow, in addition to weather conditions. All this makes it difficult to achieve the efficiencies established in the study. Still, it provides an overview of the effect of variations in COD and the possible behaviour of the plant. Thus, these diagrams can assist plant operators in selecting the most appropriate operational strategy.

Cartuja WWTP (Saragossa)

The main goal of the model-based diagnosis for the Cartuja WWTP was to carry out a comprehensive analysis of the aeration system. More specifically, to assess replacing coarse bubble diffusers with fine bubble diffusers and the effect on the air control valves’ degree of opening and the discharge pressure requirements.

The plant has three biological treatment lines, each of them divided into four aerated channels. The oversized nature of the plant allows regular operation with two lines, and for this reason the plant’s simulation was carried out in two lines. In replacing the diffusers, the first channel of each line was converted to an anaerobic zone followed by a facultative zone (with diffusers), transforming the plant into a Phoredox (A/O) configuration. The differences in the pipe network of each line that makes up the aeration system makes it necessary to simulate both treatment lines.

Under this framework, the selection of the model elements is detailed below. The CNP_Ando category was selected for the model construction; this category gathers all components and transformations that dynamically describe aerobic, anoxic and anaerobic COD biodegradation and N and P biological removal. From the unit-process model library, one primary and two secondary clarifiers (one for each line), 10 completely stirred open tank reactors (one anaerobic reactor, one facultative reactor and three aerated reactors in each line), two thickening units and a dewatering unit were selected to construct the layout.

The aeration system can be described in detail by combining the four sub-models shown in Figure 3(a), which are based on the work of Beltrán et al. (2013). The first sub-model is constituted by the selected PWM category. The objective of this sub-model is to estimate the oxygen requirements of the system or the k_l,a needed. The second sub-model is described by the O-CSTR unit-process with two gaseous phases (supplied air and open atmosphere). This sub-model describes mass transfers between supplied air and aqueous phases, and therefore it relates the oxygen requirements estimated in sub-model 1 with the gas flow provided by sub-model 3. The third sub-model is the air distribution system model. The goal of this model is to estimate the pressure loss in the distribution system depending on the gas flow that circulates through the system (estimated in model 2). This model is the only model in the library that cannot be standardized. The head losses depend closely on the gas distribution system elements of the plant under study, and it is difficult to make a generalization that satisfies all processes. Therefore, the model needs a detailed plant
layout in which the pipe lengths and diameters, the height variations, and the material specifications are defined. Finally, the last sub-model estimates the electric power supplied by the blower, which depends on the estimated air flow and pressure.

The first step in analysing the distribution system (sub-model 3) in detail is to identify all nodes or elements/accessories that compose the aeration system (Figure 3(b)). Thereafter, an energy continuity balance between each node is proposed to determine the heat losses between each element/accessory. As a result, the model provides the air flow exiting the diffuser (m/s), for a blower output pressure and valve opening degree: pressure losses in the air line due to friction caused by piping are described by the Darcy-Weisbach equation, while in the case of control valves and aeration diffusers, the pressure loss is obtained for each operating point based on the data provided in the manufacturer data-sheets. By repeating the resolution for different pressures and opening degrees, a matrix is obtained (Figure 3(c)). After the matrix is parameterized, it can be introduced as input in the standard air distribution system model (Figure 3(d)), and the simulation can be performed in order to obtain information about the valve opening degree (Figure 3(e)).

In analysing the results, Figure 3(e) shows the opening degree of the four control valves over one year of operation with fine bubble diffusers (each line has two control valves, as can be seen in Figure 4(d)). The plant has a control loop to manipulate the valves’ opening degree according to the oxygen needs and a manual control for the blowers’ output pressure. In the absence of an automatic pressure control, the plant requires supervision of the valves’ opening degree in order to study whether it is necessary to increase or decrease the pressure. When the opening degree is close to zero, the pressure may be reduced and when the valves are fully open, the process will require increased pressure to achieve the objectives of dissolved oxygen. The results show an excessive strangling of valves. After the diffusers were replaced, the air requirement dropped considerably (the new diffusers have a higher transfer efficiency), but the blower output pressure rose slightly from 0.906 bar to 0.924 bar. As shown in Figure 3(c), at low pressures, the variation of the air flow is lower. In this case, in the face of an unexpected need for oxygen, the process could lead to a valve opening of 100% and to an inability to supply the needed oxygen, revealing a slower process of manoeuvrability. This is a clear sign of air distribution system oversizing.
The conclusion reached after the study was that the air distribution system was oversized for new diffusers and that the substitution of certain pipes that made up the aeration system was necessary. Although this study was done over an existing air distribution system, the model could have been used to design the system, avoiding future design pitfalls such as oversizing blower pressure, an excessive number of diffusers or wrong pipe diameters. Thus, the model can be used not only to detect design errors or operating problems regarding the aeration system, but to also design new air distribution systems, together with their optimal control.

**Palma 1 and Palma 2 WWTPs (Palma de Mallorca)**

Palma de Mallorca’s wastewater is treated in two WWTPs, each of which receives a similar flow-rate. In the Palma 2 WWTP, COD removal and N oxidation is carried out in two channels. The COD removal channel contains three superficial turbines for the aeration and the N oxidation channel has six superficial turbines (simulated in 3 + 2 aerated zones). In the Palma 1 WWTP, COD and N removal and chemical P precipitation with FeCl₃ is carried out in a denitrification/nitrification (DN) or DNDN configuration. The process consists of an anoxic zone composed of three separate reactors, a first facultative zone, an aerobic zone composed of three reactors, a second facultative zone, and a reaeration zone. Both plants are connected. The sludge generated in Palma 2 is treated in Palma 1, creating a large amount of sludge to be treated in one plant. Furthermore, in the digestion process, a large amount of VSS is biodegraded, resulting in rejected water with high N and P concentration. In addition, to the characteristics presented in Table 1, Figure 4 shows schematically the interrelations between the Palma 1 and 2 WWTPs.

Taking into account the high sludge load treated in Palma 1 (coming from Palma 1 and 2), one of the goals of the simulation study was to assess different design and
operational scenarios for optimum N and P management in this WWTP, while trying to reduce chemical dosages. To that end, three different alternatives were considered: (1) a plant re-design for biological P removal since the plant is oversized for the current load; (2) the plant re-design in alternative (1) with simultaneous P precipitation (chemical and biological); and (3) the inclusion of a technology for struvite recovery in the sludge line in alternative (1). All these simulations required a modification in the plant layout to move from a biological COD and N removal process to a biological COD, N and P removal configuration. In the end, the A2O (anaerobic/anoxic/aerobic reactors) configuration was chosen. Although the A2O configuration is not the most appropriate process for this plant, it is the configuration that requires the fewest modifications. The operating conditions were also modified slightly in line with typical design parameters used in the A2O process (Tchobanoglous et al. 2014).

For alternative (1), the model was constructed by selecting the CNP_A and D category; two primary and secondary clarifiers, 14 completely stirred open tank reactors (nine reactors in Palma 1 and five reactors in Palma 2), two buffer tanks, two thickening units, a dewatering unit and a completely stirred closed tank reactor were selected from the unit-process library, and eleven blowers, dosage costs and electricity conversion models were selected from the cost model library.

The results obtained by simulating alternative (1) showed that the biological P removal without chemical dosage (for P removal) in Palma 1 is not possible if the water quality requirements in the effluent are to be fulfilled (see Table 2). The P stored in the phosphorus-accumulating bacteria (XPAO) and released in the digester, coupled with a high organic matter load in the sludge line (from Palma 1 and 2) and a high degree of VSS removal in the digestion process, makes the phosphorus concentration in rejected water too high (low COD/TP ratio) for Palma 1’s biological process capacity. Therefore, a minimum dosage of FeCl3 is required to fulfill the effluent requirements, which is the layout proposed in alternative (2). Simulating alternative (2) obtained the same effluent quality requirements with a dosage that was 50% less, but aeration costs (higher SRT) were higher. Still, the overall balance provided a savings of 6%. For alternative (3), a new version of the plant-wide model was constructed by replacing CNP_A and D with CNP_prec_A and D, which takes precipitation reactions into account. Unit process and cost models remained the same, and only the crystallizer unit-process for struvite precipitation and recovery was added. The wastewater characterization and biological model parameters were the same as in the previous alternatives since the only differences where related to the physico-chemical and chemical phenomena. As seen in Table 2, alternative (3) allows the removal of all FeCl3 dosing by adding a crystallizer unit for struvite precipitation. With this, it seems clear that alternative (3) could lead to an optimum solution: P and N would be removed from the Palma 1 WWTP while obtaining simultaneously struvite (a valuable product). The overall balance would provide a 50% reduction in the analysed energy, which is equivalent to 335 M€. It is worth noting that in the study, only aeration and dosing costs have been analysed, which is why, in general terms, the savings would be much smaller.

**CONCLUSIONS**

Recent works in the mathematical modelling of WWTPs show the need to update conventional models in order to facilitate the straightforward incorporation of new processes, technologies and plant configurations from the perspective of resource recovery (energy and nutrients). For this purpose, the authors propose a change from the traditional procedure for WWTP model building (based on the combination of unit-process models) to a more flexible and expandable methodology based on the combination of the compatible and mass-balanced transformations required in each case study. Several full-scale simulation studies showed the appropriateness of this proposed PWM methodology for the rigorous and straightforward construction of complex plant models. Through the case of the Galindo WWTP, the usefulness of plant-wide models in decision-making was illustrated, not
only from the standpoint of ensuring effluent quality, but also from the perspective of energy minimization. In the case of the Cartuja WWTP, detailed aeration models were needed in order to analyse the problem from a biological point of view and also from an engineering perspective. Finally, the case of the Palma 1 and 2 WWTPs showed the usefulness of the advanced model libraries in helping companies to prioritize investments. In short, these three simulation studies have demonstrated the usefulness of a compatible and complete model library for analysing and diagnosing the concerns and interests of water authorities and plant operators and to let them know the most appropriate operation criteria and prioritising investments.

Experience gained from these three and other simulation studies carried out jointly by Ceit-IK4 and Conaqua confirms the suitability of the model library approach for facing current engineering and plant operator demands in WWTPs. Moreover, the use of a standard library would greatly facilitate the development of new complementary tools that are also very important in practice, like influent characterization tools, data reconciliation tools, etc.

Based on this, authors encourage the creation of collaboration and consensus spaces where research groups and engineering/software companies can work together on the construction and upgrade of model libraries that compatible, modular, expandable and sufficiently flexible.

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