Activated sludge modeling of Vale Faro Waste Water Treatment Plant

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ABSTRACT

Activated sludge treatment is a biological process widely used to remove organic pollutants and nutrients from wastewater since it is very efficient and it is the most economical used process. It has been the subject of detailed metabolic studies of inherent biological processes, which has allowed the development of several mathematical models, known as ASM (Activated Sludge Model).

The main objectives of this study are the model calibration in Vale Faro waste water treatment plant (WWTP) and the optimization of the operating conditions in the biological stage of the WWTP. The study focused on the aeration step, which is responsible for the highest energy consumption in the system. Several simulations have been performed, both under steady-state conditions and with dynamic dissolved oxygen set points in order to achieve the best optimal conditions. The possibility of changing the diffuser system was also evaluated, in order to increase the aeration efficiency, the performance level of the treatment system and the reduction of the energy consumption.

In this paper, the Mantis model, an adapted model from ASM1, was used. The model was run in the mathematical simulation software GPS-X (version 6.4) of Hydromantis.

The model was applied to the Vale Faro WWTP, one of the larger facilities in the Algarve, which discharges its effluent near the bathing area. Given the seasonality that the WWTP is subject, it became necessary to develop two distinct layouts and models to describe the behavior of the installation, in high and low seasons.

The modeling results allowed us to describe the WWTP behavior and optimize aeration by changing the OD set point. Simulations indicate a reduction of energy consumption (about 35%) and related costs, by replacing the diffusers.

This study contributes to validate the use of ASM mathematical models in full-scale WWTP, namely in the optimization of the aeration step.

Keywords: activated sludge; mathematical modeling; aeration optimization

1. INTRODUCTION

The Wastewater Treatment Plant (WWTP) have a key role in maintaining public health and preserving the quality of the receiving environment, minimizing water pollution problems caused by untreated wastewater discharge into receiving environment.

Regulatory instruments designed to protect the quality of natural waters, act by establishing standards and discharge conditions, defined depending on the type of the receiving environment. For each treatment plant, a discharge license is defined, which may contemplate emission limits values (ELVs) for the physical, chemical and microbiological parameters.

The physicochemical parameters that typically have set discharge limits are the biochemical oxygen dissolved after 5 days (BOD5), chemical oxygen demand (COD), which represents the organic load and total suspended solids (TSS) and may also be included nutrients, nitrogen (N) and phosphorus (P) in treatment plants discharging into sensitive areas to
eutrophication. Emission limit values (ELVs) can be also defined for microbiological parameters, specifically fecal coliforms and E. coli.

The need for control pollutants discharges in the receiving environment as well as the need to increase the predictability biological treatment processes behavior has motivated in large part, the recent developments in modeling and management of wastewater treatment systems.

The increasing knowledge of the biological degradation treatment mechanisms by activated sludge processes resulted in the publication of some mathematical models currently used as tools for planning, design, analysis and processing operation infrastructures. The modeling is therefore an essential part of the wastewater treatment plant design and operation (Grau et al., 2007).

Mathematical modeling of microbiological treatments in activated sludge process was introduced in the early 70s, has undergone various renovations until they reach the current matrix models developed for nearly 20 years, the International Water Association, IWA. Current models in Anglo-Saxon terminology, "Activated sludge models". ASM, prove to be excellent tools to modeling carbon oxidation processes, nitrification and denitrification and biological phosphorus removal (Nuhoglu et al., 2005). These models have been applied in many commercial software modeling and simulation of the biological processes dynamic behavior (Gernaey et al, 2004), among which stand out the GPS -X, SIMBA, EnviroSim, BioWin and AQUASIM.

As part of this work GPS-X Simulator (version 6.4), developed by a Canadian company, Hydromantis, was selected and we used the activated sludge model, the Mantis. Mathematical modeling applied to complex systems such the present work, is a gain in the operation and management infrastructure, to the extent that it helps in understanding the interconnection of many variables, their behavior and the system’s performance. Through mathematical modeling, for example, a preventive action can be taken at the level of the installation behavior towards certain inflow conditions. It can also function as an assistance tool for management and control the process treatment process, allowing to optimize the various operating parameters, namely, sludge age, recirculation reasons, DO (dissolved oxygen) set points, ammonia, nitrates, minimizing the energy consumption while maintaining, or if possible improving, the final effluent quality.

The advantages associated with the use of ASM in WWTP does not stop there, because in addition to allowing optimization of the treatment plant operating conditions, it can be used to support investment decisions, including treatment plant rehabilitation and the acquisition of appropriate equipment.

Energy efficient use is a worldwide priority, leading the company to take action and to seek solutions that reduce energy costs in a sustainable way. Although the contribution of urban water services to the energy consumption on a global scale is very low (about 7 %), energy issues are vitally important in its activity, representing a significant fraction operating consumption level (Hoffman, 2012).

The intensive treatment systems, such as activated sludge systems, are very efficient in wastewater treating being, however, associated with a high energy consumption.

Aeration is essential in biological treatment processes, since oxygen is essential for the biochemical processes such as organic and nitrogenous oxidation, further promoting mixed liquor stirring and mixing and thus, contact between the microorganisms and the substrate.

The oxygen demand (AOR - Current Oxygen Requirement) can be estimated by the sum of the oxygen required for cell synthesis, for endogenous respiration and for nitrification.

However, to taking in consideration the oxygen transferred to the wastewater (OTR) which is not consumed by the microorganisms, given that AOR considered for design and are thus not accounted for excess oxygen. The OTR thus corresponds to the oxygen transfer rate and the AOR the amount of oxygen required for biological processes triggered in the biological reactor. The OTR project level is equal to the AOR.

On the other hand, the diffusers systems should be replaced with some frequency. After some use, there is a significant decrease in the power transfer factor (α factor), with the aging of the diffusion membrane. It is noted that the α factor after 2 years of use, the membrane reaches the approximate value of 0,3. It was precisely the amount considered for the simulation of oxygen transfer in diffusers currently installed. On the other hand, the α factor considered for the new diffuser, was 0,5, value typically defined in catalog for the new diffuser.
2. CASE STUDY

The Vale Faro Wastewater Treatment Plant (WWTP) was built in 1980 and was rebuilt in 2002, to allow the nutrient removal and treated wastewater reuse for the service water production. Although the new WWTP contemplates changes to the nutrient removal, discharge license only requires compliance for the organic matter (COD, BOD5) and Escherichia coli (Table 1). The plant is designed for an average daily flow of 24,310 m³/day and a population of 130,000 eq. hab.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ELV</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBO₅</td>
<td>25</td>
<td>mg/L</td>
</tr>
<tr>
<td>CQO</td>
<td>125</td>
<td>mg/L</td>
</tr>
<tr>
<td>Escherichiacoli</td>
<td>2000</td>
<td>NMP/100 mL</td>
</tr>
</tbody>
</table>

Currently all treated effluent in Vale Faro WWTP is discharged into the Atlantic Ocean, which is the reason why in the discharge license installation there is no need to remove phosphorus.

3. METHODOLOGY

This work has included the following phases:
Phase 1: Description of the Vale Faro WWTP (WWTP with activated sludge systems, low load with extended aeration, with two distinct lines of treatment, to meet the 2 seasonal features of this WWTP), introduction of the 2 treatment regime in the model, representative of the two seasonal periods.
Phase 2: Relevant data collection and processing, such as flows, inflow conditions and respective physical-chemical parameters, WWTP operational parameters (set points OD, sludge recirculation, age sludge, etc.), and conducting mass balances.
Phase 3: Mathematical model calibration (Mantis), considering the carbon and nitrogen biological removal for the high and low season. For this it is necessary to resort to the history of affluent weekly results (COD and respective frSi organic fractions frSs, frXi, phosphorus, total nitrogen), and the respective entry data for the model (recirculation reason average, extracted sludge, thickening and dehydration efficiency). To calibrate the model, the sludge production was compared with the simulated sludge production, and we considered that the model is calibrated if the difference between simulation and experimental results, were within the limits indicated by the IWA. To this end, it has become necessary to adjust some parameters including, thickening efficiencies as well as dehydration and clarification percentage in the secondary sedimentation tank.
Stage 4: Model validation by comparing the simulation and experimental results on the final effluent quality, the total suspended solids concentration in the reactor and the sludge production, in years other than those used in the calibration.
Phase 5: Simulation in steady state at different DO set points, to obtain associated energy consumption
Phase 6: Dynamic Simulation and optimization of energy consumption throughout a day.
Phase 7: Study of the foreseeable increase in oxygen transfer efficiency obtained by changing the air diffusers.

4. RESULTS

4.1 MODEL CALIBRATION

The model calibration is performed in an iterative manner. The first model is evaluated and the results are interpreted and compared with the experimental results. Often, the first simulations generate results that are not consistent with those observed in reality. At this stage, detailed treatment plant knowledge, as well as its management and operation, are an asset in model calibration, because they allow us to exclude unreliable values and to interpret the data with greater confidence.
Thus, certain model parameters have to be adjusted knowing some plant operation details. The formulation cycle is again repeated until agreement between simulation and reality is obtained.
Calibration was always done by running the model for a number of days sufficient to obtain representative averages for the high and the low seasons.
In this case, we ran the model about 100 days, at steady state to the average values of high season (July to September 2013 and 2014), and of the low season (November to May, 2013 and 2014).

In the tables, the main parameters to be checked during model calibration for the high and low season are represented (Tables 2 and 3).

Table 2 - Model calibration for the high season, by comparing the results simulated by GPS -X and actual results (July to September 2013 and 2014), Vale Faro WWTP.

<table>
<thead>
<tr>
<th>Calibration Parameters</th>
<th>Simulated Values</th>
<th>Real values</th>
<th>Deviation</th>
<th>Acceptable error IWA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sludge volume(m3/day)</td>
<td>25.6</td>
<td>25.6</td>
<td>0.0%</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Reactor SST(mg/L)</td>
<td>3832</td>
<td>3904</td>
<td>1.8%</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Treated effluent COD (mg/L)</td>
<td>42.1</td>
<td>41.7</td>
<td>0.9%</td>
<td></td>
</tr>
<tr>
<td>Treated effluent SST (mg/L)</td>
<td>7.1</td>
<td>7.1</td>
<td>-0.04 mg/L</td>
<td>&lt;5mg/L</td>
</tr>
<tr>
<td>Treated effluent BOD5 (mg/L)</td>
<td>2.3</td>
<td>12</td>
<td>81.1%</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 - Model calibration for the low season, by comparing the results simulated by GPS -X and actual results (November to May, 2013 and 2014), Vale Faro WWTP.

<table>
<thead>
<tr>
<th>Calibration Parameters</th>
<th>Simulated Values</th>
<th>Real values</th>
<th>Deviation</th>
<th>Acceptable error IWA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sludge volume(m3/day)</td>
<td>12.2</td>
<td>12.0</td>
<td>1.7%</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Reactor SST(mg/L)</td>
<td>3939</td>
<td>3922</td>
<td>0.4%</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Treated effluent COD (mg/L)</td>
<td>40.6</td>
<td>40.0</td>
<td>1.5%</td>
<td></td>
</tr>
<tr>
<td>Treated effluent SST (mg/L)</td>
<td>9.8</td>
<td>8.1</td>
<td>1.7mg/L</td>
<td>&lt;5mg/L</td>
</tr>
<tr>
<td>Treated effluent BOD5 (mg/L)</td>
<td>2.6</td>
<td>12</td>
<td>83.6%</td>
<td></td>
</tr>
</tbody>
</table>

4.2 MODEL VALIDATION

The model validation was performed with a sample data of periods different than those used in calibration, In this case the most recent results (year 2015 for the high and low season).

Next, the values obtained in model validation for both seasons are presented (Table 4 and 5).

Table 4- Model validation for the high season, by comparing the simulated and actual results from July to September 2015.

<table>
<thead>
<tr>
<th>Calibration Parameters</th>
<th>Simulated Values</th>
<th>Real values</th>
<th>Deviation</th>
<th>Acceptable error IWA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sludge volume(m3/day)</td>
<td>22.0</td>
<td>22.5</td>
<td>-2.22%</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Reactor SST(mg/L)</td>
<td>3.348</td>
<td>3.326</td>
<td>0.66%</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Treated effluent COD (mg/L)</td>
<td>36.3</td>
<td>36</td>
<td>0.83%</td>
<td>5mg/L</td>
</tr>
<tr>
<td>Treated effluent SST (mg/L)</td>
<td>6.2</td>
<td>4.0</td>
<td>2.20</td>
<td></td>
</tr>
<tr>
<td>Treated effluent BOD5 (mg/L)</td>
<td>2.5</td>
<td>12</td>
<td>-79.17%</td>
<td></td>
</tr>
</tbody>
</table>

Table 5- Model validation for the low season, by comparing the simulated and actual results from November to May 2015.

<table>
<thead>
<tr>
<th>Calibration Parameters</th>
<th>Simulated Values</th>
<th>Real values</th>
<th>Deviation</th>
<th>Acceptable error IWA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sludge volume(m3/day)</td>
<td>12.2</td>
<td>12.0</td>
<td>1.3%</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Reactor SST(mg/L)</td>
<td>3705</td>
<td>3737</td>
<td>0.9%</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Treated effluent COD (mg/L)</td>
<td>39.4</td>
<td>39.2</td>
<td>0.4%</td>
<td></td>
</tr>
<tr>
<td>Treated effluent SST (mg/L)</td>
<td>8.9</td>
<td>10.7</td>
<td>-1.80</td>
<td>&lt;5mg/L</td>
</tr>
<tr>
<td>Treated effluent BOD5 (mg/L)</td>
<td>2.5</td>
<td>15</td>
<td>83.3%</td>
<td></td>
</tr>
</tbody>
</table>
4.3 AERATION OPTIMIZATION

4.3.1 Steady State Simulation

In order to validate the simulated energy consumption, several simulations for the 2014 peak season average conditions were run and compared with the amounts consumed by blowers, for the same period. The consumed values were obtained by calculation, taking into account the blower power and the respective operating hours. The energy consumed by blowers for high season in 2014 was 380 kW, a value close to the value obtained by the model for the current operation set point at Vale Faro WWTP, which was 388 kW.

Various scenarios were tested by analyzing the effect on the final effluent, of lowering the dissolved oxygen (DO) in aerated areas. The figures below show the evolution of the physical and chemical parameters of the treated effluent, for different oxygen set points, for the high (Figure 1) and low season (Figure 2).

![Figure 1 - COD and SST variation along the high season, for various dissolved oxygen set points.](image1)

![Figure 2 – COD and SST variation along the low season, for various dissolved oxygen set points.](image2)

<table>
<thead>
<tr>
<th>Calibration Parameters</th>
<th>DO= 1 mg/L</th>
<th>DO= 0.8 mg/L</th>
<th>DO= 0.6 mg/L</th>
<th>DO= 0.4 mg/L</th>
<th>DO= 0.2 mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTR (kg/h)</td>
<td>354</td>
<td>345</td>
<td>326</td>
<td>311</td>
<td>267</td>
</tr>
<tr>
<td>Aeration energy (kW)</td>
<td>394</td>
<td>376</td>
<td>349</td>
<td>326</td>
<td>275</td>
</tr>
<tr>
<td>Costs (Euros/day)</td>
<td>692</td>
<td>653</td>
<td>608</td>
<td>570</td>
<td>485</td>
</tr>
</tbody>
</table>
### Table 7- Energy consumption and cost for various dissolved oxygen set points, under low season affluence average conditions, in the period 2013-2015.

<table>
<thead>
<tr>
<th>Calibration Parameters</th>
<th>DO= 1 mg/L</th>
<th>DO= 0.8 mg/L</th>
<th>DO= 0.6 mg/L</th>
<th>DO= 0.4 mg/L</th>
<th>DO= 0.2 mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTR (kg/h)</td>
<td>188</td>
<td>135</td>
<td>128</td>
<td>114</td>
<td>81</td>
</tr>
<tr>
<td>Aeration energy (kW)</td>
<td>178</td>
<td>155</td>
<td>142</td>
<td>117</td>
<td>88</td>
</tr>
<tr>
<td>Costs (Euros/day)</td>
<td>309</td>
<td>270</td>
<td>249</td>
<td>206</td>
<td>159</td>
</tr>
</tbody>
</table>

### Table 8- Energy costs comparison for the current set point and the optimal set point (0.4 mg/L), based on the period from 2013 to 2015.

<table>
<thead>
<tr>
<th>Calibration Parameters</th>
<th>Current DO = 1 mg/L</th>
<th>Optimized DO = 0.4 mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy costs High season (Euros / 4 months / year)</td>
<td>83.040</td>
<td>68.400</td>
</tr>
<tr>
<td>Energy costs Low season (Euros / 8 months / year)</td>
<td>74.160</td>
<td>49.440</td>
</tr>
<tr>
<td>AnnualCosts (Euros/year)</td>
<td>157.200</td>
<td>117.840</td>
</tr>
<tr>
<td>Cost Optimization (Euros/year)</td>
<td>39.360</td>
<td></td>
</tr>
</tbody>
</table>

#### 4.3.2 Dynamic State Simulation

In dynamic state the model allows optimization of the air consumption and respective costs over a day, obtained by varying aeration rate during that period.

The dynamic simulation main purpose is to optimize the DO set points throughout the day. This can go through increasing the DO concentration before the peak times, periods in which the inflow rate increases significantly.

In order to understand how the change of the set point throughout the day, can influence the treatment process, the model was run for the high season at the highest flow rate of 2015 (17.966 m³ / day), and the treated effluent quality was simulated over 10 days. The simulation was performed for four scenarios: with variable DO set point along the day, as well as constant DO set points, current DO (1 mg / L) and optimized DO (0.4 mg / L).

The various periods considered as well as the respective set points for the various simulations are presented in Table 8.

#### Table 8- Different dynamic simulations by changing the set point throughout the day.

<table>
<thead>
<tr>
<th>Daily Periods (h)</th>
<th>Sim_1</th>
<th>Sim_2</th>
<th>Sim_3</th>
<th>Sim_4</th>
<th>Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2 am</td>
<td>0.6</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.069607</td>
</tr>
<tr>
<td>2-6 am</td>
<td>0.6</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.05856</td>
</tr>
<tr>
<td>6-7 Horas</td>
<td>0.8</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.06961</td>
</tr>
<tr>
<td>7 - 9:15 Horas</td>
<td>1</td>
<td>0.6</td>
<td>0.5</td>
<td>0.5</td>
<td>0.097422</td>
</tr>
<tr>
<td>9:15 -12:15 Horas</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.108934</td>
</tr>
<tr>
<td>12:15 - 24 Horas</td>
<td>0.8</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
<td>0.09742</td>
</tr>
</tbody>
</table>

The final effluent quality was simulated for the various scenarios present on Table 8 and for the constant DO set points (1 and 0.4 mg/L) as shown on Figure 3.
Figure 3 – COD and BOD5 evolution in the treated effluent during 10 days simulation for the various set point changes over days, as well as for constant set point (0.4 and 1 mg/L).

Subsequently determined whether the costs for the various scenarios set points, compensates the DO set point changes throughout the day implementation (Figure 4).

Figure 4 – Annual costs associated with aeration process simulations for various dynamic and steady-state (DO set point 0.4 and 1 mg/L).

4.3.3 Change of diffusers

In order to verify the economic feasibility of the replacing diffusers system two different simulations were run, that reproduce the current and the new situation with new diffusers. It was considered for this purpose, the $\alpha$ factor increased from 0.3 to 0.5, according to Figure 5.

Figure 5 – Alpha factor evolution with operating times (Rosso, 2013).

By analyzing the previous figure, it appears that there is a significant decrease in the energy transfer factor ($\alpha$ factor), with an aging diffusion membrane. It is noted that the $\alpha$ factor after 2 years of use, reaches the approximate value of 0.3. It was precisely the value considered for the oxygen transfer simulation of the diffusers currently installed. On the other hand, the $\alpha$ factor considered for the new diffusers, was 0.5, value that is typically defined in catalog for a new diffuser.

Table 9 presents the values obtained for the simulations with the old and new diffusers, for two different periods (high and low season), using the average data from 2013 to 2015.
Table 9- Change in energy cost, with old and new diffusers.

<table>
<thead>
<tr>
<th></th>
<th>Old Diffusers</th>
<th>New Diffusers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High season</td>
<td>Low season</td>
</tr>
<tr>
<td>Aeration energy costs (Euros)</td>
<td>83.040 (4months)</td>
<td>74.160 (8months)</td>
</tr>
<tr>
<td>Annual savings (Euros/years)</td>
<td>54.540</td>
<td>54.540</td>
</tr>
</tbody>
</table>

For the design conditions, for which the treatment plant was built, the oxygen transfer rate (OTR) is about 692 kg O2 / h for the average inflow conditions and 1255 kg O2 / h to the peak conditions. For the peak conditions, it is necessary to provide an air flow of 24.123 m3 / h flow. Considering the minimum diffuser unit capacity (7 Nm3 / h), one concludes that 3446 diffusers are required, corresponding to a62,373 Euros investment, for a18.1 Euros / diffuser unit cost (OTT Group 2014).

The investment is recovered after 1 year and 2 months (54,540 Euros annual savings).

5. CONCLUSIONS

Mathematical modeling is an important tool for the optimization of the operation of wastewater treatment systems, providing useful information regarding operating strategies without the need of more investments.

The two models, that describe and simulate the wastewater treatment in the Vale Faro WWTP for two seasons, high and low, were validated and calibrated. Mantis model was the chosen ASM model since it described very well the behavior of the activated sludge system.

Regarding the optimization of the aeration, it has been found through simulation in steady state, that there is currently an excess of oxygen supplied to the reactor. The simulation results show that for the set point of 0.4 mg / L, there is a significant reduction in energy costs associated with the aeration step, decreasing from 157 thousand EUR per year currently consumed to 118 thousand euro, which corresponds to a reduction of 25 %, while the final effluent quality was kept within the regulatory limits, for both seasons. With a dissolved oxygen concentration in the bulk liquid of 0.4 mg / l the supplied amount of oxygen (OTR) approaches as closely as possible to the real needs of oxygen (AOR).

Dynamic simulation showed that increasing the dissolved oxygen concentration during periods of low energy tariff, immediately before the periods of high energy tariff just leads to a slightly decrease in the energy consumption.. The reason from this behavior is that in Vale Faro WWTP, as in other wastewater treatment systems, the periods of higher loads and inflows coincide with the periods where the energy tariff is higher. Decreasing the dissolved oxygen concentration in these periods can easily lead to a deterioration of the effluent quality.

Regarding the diffusers replacement, several studies showed that there is an obvious decrease in the alpha factor with the age of the use diffuser system, reaching half of the initial value just after about 2 years of operation. That is, the older the diffusers, the lower the amount of oxygen transferred for the same power supplied by blowers, hence the higher the energy consumption.

The acquisition of a new diffuser system, the tubular type, for instance, with an initial investment cost of about62,373 euros, allows annual energy savings of about 54,540 euros, and investment cost recovery just after 1 to 2 months.

Acknowledgements

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References

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