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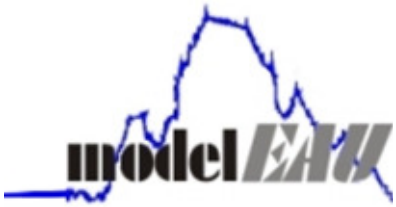

Implementation of a dynamic cost calculation module for Avedøre WWTP using WEST

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ABSTRACT

Water management and treatment are increasingly becoming big issues. For wastewater treatment, legislations are getting more restrictive. Plant operators have to optimise their processes. The use of modelling to optimise plant operation is more and more common because it is reliable and fast. Besides reaching the limit fixed by legislation, WWTP operators, like others industries, try to minimize operational costs as much as possible.

This work presents results of the implementation of a cost evaluation module into the Avedøre WWTP model already available in the WEST® modelling platform. The goal of the project was to estimate three different classes of cost: i) taxes on nutrients ii) chemical consumption and iii) energy consumption. The energy cost calculation was to be based on an energy cost chart with costs for electricity depending on the time of day.

All objectives of the project have been fulfilled and the cost module provides good estimations of operational costs selected. Some fine tuning is still required and the model should be tested with more real data to verify its robustness.

PREFACE

This project has been realised mutually with Avedøre WWTP, Lund University and model*EAU*. Most of the modelling work was done at Lund University whereas the report compilation took place at Université Laval in Québec.

I would like to thank Professor Ulf Jeppsson from Lund University for his great hospitality, his precious help and advices during my stay in Sweden. I would also like to thank Erik Lindblom, from Denmark Technical University, for his technical support.

I would also like to thank people from Avedøre WWTP and Damhusåen WWTP who made my stay possible. I would like to especially thank Dr Bo N. Jacobsen for allowing me do this stimulating project and Anitha K. Sharma for her great availability to answer my questions and to give me all the info I needed.

Finally, I would like to thank model*EAU*'s people, especially my director Peter A. Vanrolleghem and my supervisor Dr. Leiv Rieger for all the time they spent to organise this project, which was only one part of a long stay in Europe. I appreciate the trust they put in me by sending me to different organisations, companies and research institutes to represent the model*EAU* group and making this entire trip possible.

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1. GENERAL INTRODUCTION

1.1 Context

Problems due to water quality have increased significantly during the last decades. In the wastewater treatment field, operators have to deal with legislations that are more and more restrictive and therefore constantly have to optimise their plants. However, it could be hazardous to change control settings or operation setups of a plant, as it could result in losing control of the process. Also, due to the reaction time of some operating parameters, e.g. sludge retention time, it could take days or even weeks to stabilize and observe effects of the change of the settings. To prevent that, pilot plants are often used. Basically they represent a scale down of the full plant. Experiments can be carried out without disturbing the full plant, but pilot plants are expensive to operate (equipment, workforce) and the problem of stabilization time remains.

That is why modelling is more and more used for wastewater treatment plant optimisation. It could be time consuming to build a model, but as soon as it is done, running simulations is cheap, fast and results are reliable, and it is possible to do scenario analysis of complex systems. Avedøre WWTP, in collaboration with Lund University, developed such model for their plant.

The model*EAU* group joined the project to help with the development. After a meeting with people involved in the project, the task attributed to model*EAU* was to develop a cost estimation module and implement it on top of the actual WWTP model. The goal was to evaluate dynamic costs, such as taxes on effluent, chemical additions and energy consumption.

In other sections of this chapter the particular process used at Avedøre WWTP, the Bio-denitro^{tm} process, will be explained and the Avedøre WWTP will be presented. Afterwards, a description of the activated sludge model and the WEST® modelling platform will be given and finally the project will be described. In the second chapter, all

implementation steps of the cost module will be described. In the third chapter, the results and their interpretation will be discussed. The fourth chapter will describe the cost module utilisation. Finally the last chapter will contain the conclusions.

1.2 Bio-denitro^{tm} process

The Bio-denitro^{tm} process is complex to operate. The nutrient removal processes involved (nitrification, denitrification, etc.) are the same as those in other types of wastewater treatment plants, but the Bio-denitro^{tm} process is complex in its operation and control and therefore offers increased flexibility and control authority. On the other hand it allows to reach low effluent nutrient concentrations, lower than 8 mg/L of total nitrogen (Tchobanoglous *et al*., 2003). In Denmark, in addition to respecting limits set by law, WWTP operators have to pay for each kilogram of nutrient released into the recipient.

A Bio-denitro^{tm} treatment line has two tanks in parallel, in the case of Avedøre WWTP two oxidation ditches. The whole plant has four lines, so eight reactors. In the beginning, the control was implemented in one line (the master line) and the control actions were duplicated for the other three lines (slave lines). Recently (2006), the control system STAR (Nielsen and Onnerth, 1995) has been implemented to a second line. Since then, the plant has two master lines and two slave lines. Reactors can be operated in parallel, in series or in batch in aerobic, anoxic and anaerobic (for enhanced biological phosphorus removal) phases. Figure 1 shows the typical sequence during nutrient removal.

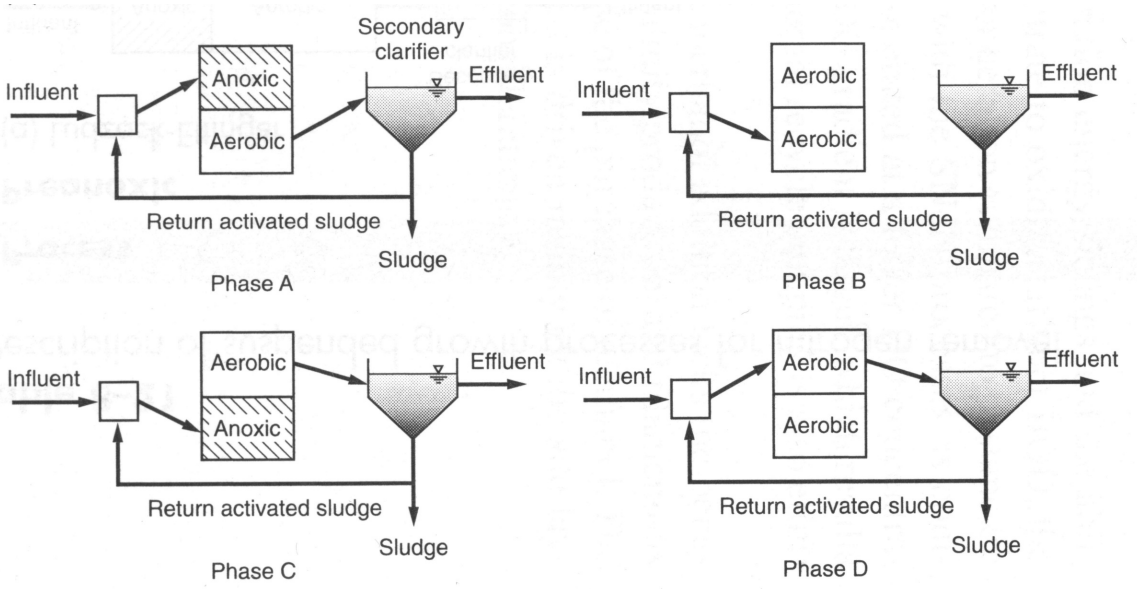


Figure 1: Typical phases of a Bio-denitro[tm] process
(Tchobanoglous *et al.* , 2003)

Typically, nutrient removal is done in four phases (see Figure 1). During phase A, the influent is sent to the tank which is in the anoxic phase. Similar to a SBR reactor, the nitrate remaining in the tank is coming from the last aerobic phase. Then, the effluent is going to the aerobic phase and to the secondary settler. During phase B, the tank which was in the anoxic phase is isolated and operated in aerobic mode. The influent is redirected to the other tank which is still in the aerobic phase. Then phase C is a mirror of phase A, i.e. the influent is still going to the same reactor as in phase B, but the reactor has switched to anoxic conditions. Finally, phase D is the same as phase B but it is the other reactor which is isolated. Those 4 steps are the typical phases used, but there are many more configurations possible.

1.3 Presentation of Avedøre WWTP

Avedøre WWTP is located south-west of Copenhagen. The design capacity of the plant is 345 000 population equivalents. The plant is owned by 10 municipalities west of Copenhagen. The wastewater treatment part has 4 primary settlers of 4000 m^3 each, 4 pairs of activated sludge tanks of 8000 m^3 each reactor and 8 secondary settlers of 5300 m^3. In 2006 Avedøre WWTP treated 25.9 M m^3 of wastewater. Table 1 shows the amount of nutrients, COD and BOD_5 received and discharged at the plant in 2006.

Table 1: Composition of the inlet and the outlet of Avedøre WWTP in 2006 (source: Avedøre WWTP)

Variable	inlet		outlet		Treatment efficiency
	(ton)	(mg/L)	(ton)	(mg/L)	(%)
COD	13210	510,0	720	27,8	94,5
BOD_5	5480	211,6	80	3,1	98,5
Nitrogen	1080	41,7	140	5,4	87,0
Phosphorus	204	7,9	18	0,7	91,2

In addition to the wastewater treatment part, the plant has a complete sludge treatment line. The sludge treatment receives approximately 930 m^3 per day of sludge at 3.3% density from the WWTP. The sludge is first going to the anaerobic digesters; four of 6000 m^3 each. The sludge is going directly in digesters, thickeners are used only for primary sludge and sand and grid filters residuals. After a retention time of 25-30 days at 32°C, the sludge is leaving the digester at a density of 2% before entering the dewatering and incineration treatment. The biogas produced by anaerobic digestion is converted into energy; this power production is covering 43% of the energy needed at the plant. Figure 2 shows the complete diagram of Avedøre WWTP.

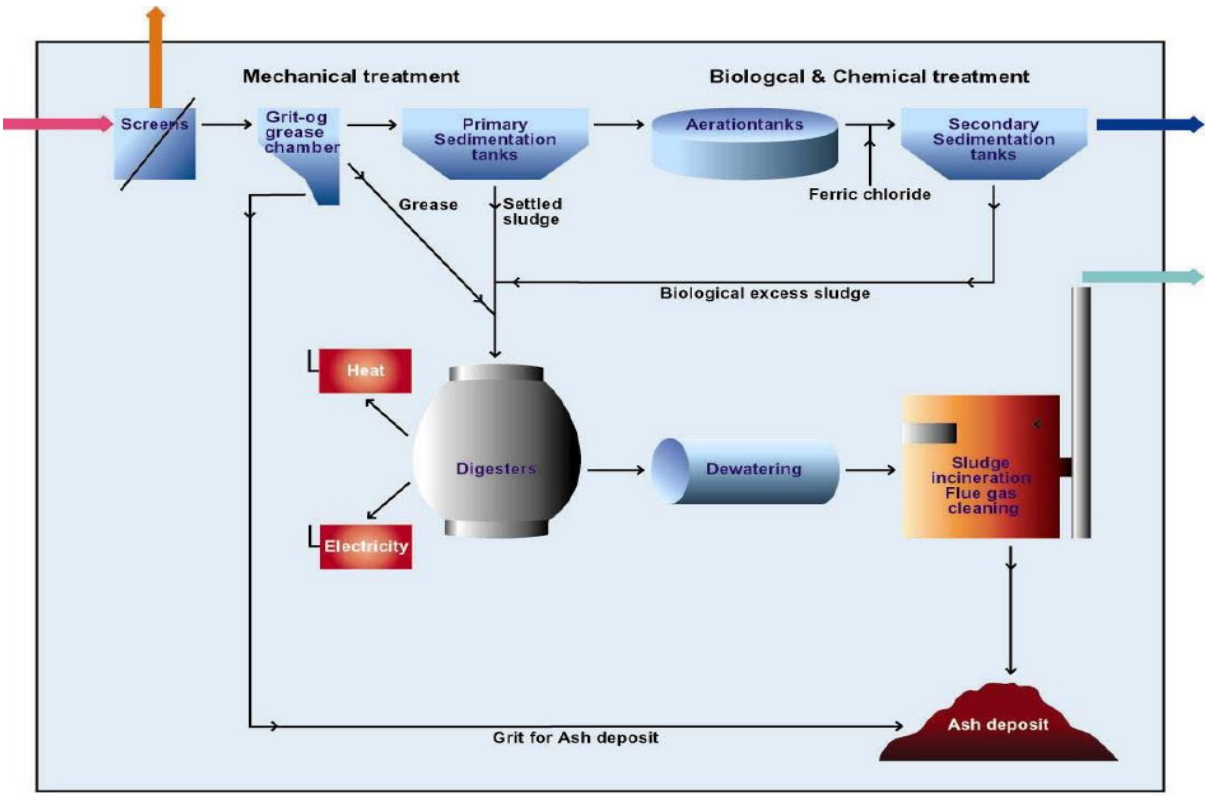


Figure 2: Avedore WWTP diagram (source: Avedore WWTP)

1.4 Activated Sludge Model and WEST® modelling platform

Modelling is more and more used in wastewater treatment. Modelling allows end-users to predict behaviours of the plant, to test different setups and control settings without the consequences that may occur if they were tested on the real plant. Different software platforms for wastewater treatment modeling are available, but the fundamental mathematical models are mostly the same. The responsible of the Avedøre WWTP chose to use the WEST® platform.

For the Bio-denitro™ process, the model used is the activated sludge model ASM2d (Henze *et al.*, 2000). The most significant change from ASM1 to ASM2 is the fact that the biomass now has a cell internal structure, and therefore its concentration can not simply be described with the lumped parameter describing biomass concentration. This extension is necessary to include biological phosphorus removal. In addition, the ASM2

model includes two chemical processes to model chemical precipitation of phosphorus. The ASM2d model is a minor extension of the ASM2 model. It includes two additional processes to take into account the fact that phosphorus accumulating organisms can use cell internal organic storage products for denitrification. Finally, the used WEST® inplementation ASM2dTemp model is also taking into account the temperature effects on the kinetics.

The Avedøre wastewater treatment plant model has been built by Erik Lindblom from Denmark Technical University, in collaboration with Ulf Jeppsson and Christian Rosen from Lund University. The Avedøre wastewater treatment plant model includes one treatment line of the whole plant, i.e. one primary settler, two activated sludge tanks, one chemical precipitation of phosphorus and one secondary settler (see Figure 3). For the time being, the sludge treatment chain is not included in the WWTP model.

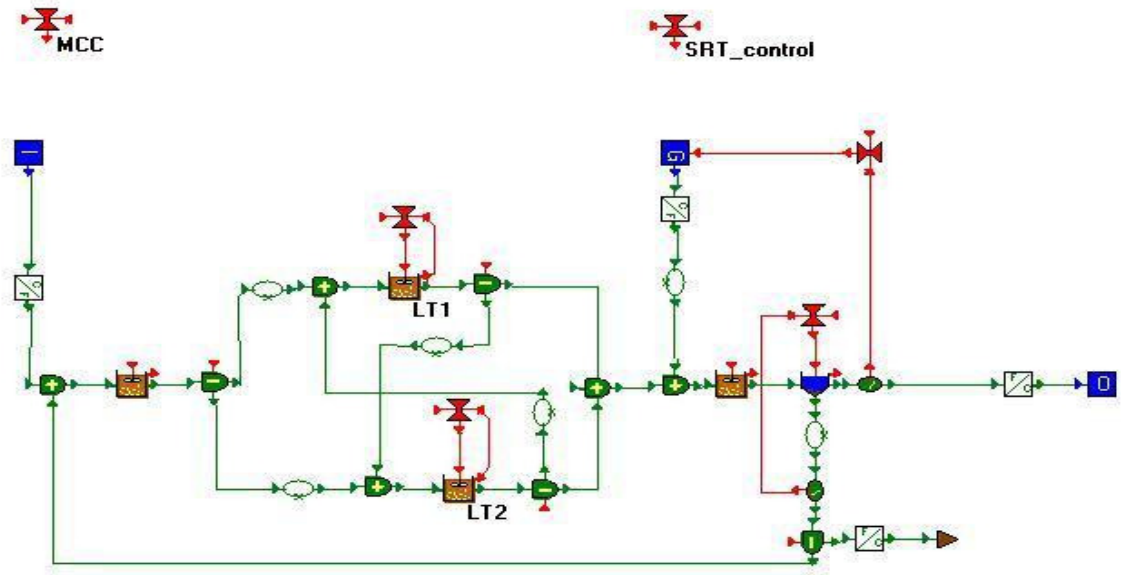


Figure 3: Model of the Avedøre WWTP in WEST®

1.5 Presentation of the project

As other industries, WWTP operators try to minimize operational costs. Modeling is more and more used in wastewater treatment because it allows operators to test the effect of changing control parameters, to predict the behaviour of the plant under certain circumstances and this without affecting the plant. If the model is accurately representing reality, it could be used to estimate operational cost and then by running different scenarios, it is possible to find ways to reduce those costs.

The goal is to introduce a cost calculation tool in the Avedøre WWTP model developed by Erik Lindblom. After a meeting with people from Lund University and Avedøre WWTP, an outline of the project was set up (see minutes of the meeting in Annex A). Cost has been separated in three classes: the first one is about taxes. In Denmark, in addition to being required to discharge effluent that is containing nutrient concentrations below a certain concentration, the plant has to pay taxes for the discharge of each kilogram of total nitrogen and phosphorus and also for biological oxygen demand (BOD). The second class of costs concerns chemical consumption; it includes chemicals for phosphorus precipitation, for carbon addition and also the cost to treat the additional inert sludge coming from the phosphorus precipitation. The last cost class includes energy consumption, i.e. aeration energy and returned activated sludge (RAS) pumping costs.

Other criteria that have been considered in the project are that costs have to be calculated directly in the WEST® simulation environment, in other words, that the end-user does not have to export and/or manipulate data to get results. Also, Danish Kronor (DKK) should be used as default currency instead of Euro. Swedish Kronor (SEK) and Canadian Dollar (CAD) were to be included for use of the WEST® model in other countries. Finally, the energy cost must be calculated according to a tariff chart describing how energy costs depends on the time of day.

2. MATERIALS AND METHODS

This chapter describes materials, tools and data used to achieve the objectives of the project. First, a small introduction of the simulation platform WEST® will be given. Then a step-by-step description of the work done to implement parameters, variables and equations will be presented. The last section will describe how to use the module and how to change parameters. It also includes an overview of the precautions to be taken before running simulations.

2.1 WEST®

It was stated above that WEST® includes the ASM models for the activated sludge units. But this platform also includes models for primary and secondary settlers, sensors, controllers, sludge treatment and a cost module. The emphasis will here be put on this cost unit. In this version of WEST® elements included in the basic cost unit are: pumping energy (up to ten pumps), aeration cost, waste pumping energy (up to two pumps), mixing and sludge treatment cost. Due to the simplicity of the existing model, parameters, variables and equations had to be implemented and/or modified.

To be modified:

- Aeration Energy cost
- Pumping energy cost

To be added:

- Taxes on nutrients
- Chemicals dosage
- Additional inert sludge
- Energy cost tariff chart

It will be explained how this has been done but first a short description of WEST® will be given.

2.1.1 Model Editor

The model editor is the environment where parameters and variables are created and defined; it is where all equations are written. For standard models, the end-user usually does not have to go into this environment, but in the present case the major part of the work has to be done in it. Four kinds of model constituents can be found in the model editor, three of them are variables: independent, interface and state variables. Time is the only independent variable. Values of interface variables are coming from other units of the model, e.g. flow rate, temperature, concentration, etc. State variables are the results of the calculations, e.g. aeration energy, pumping cost, etc. Finally, there are also parameters, which are set by the user and are time independent, e.g. tank volume, cost factor, conversion factor, etc.

2.1.2 Configuration Builder

In this environment, the end-user is building a model by adding units such as activated sludge units, settlers, controllers and connecting them with pipes and/or signal lines. It is also in this environment that the end-user is selecting the individual models for each unit.

2.1.3 Experimentation Environment

In this environment the end user can run simulations, create graphs, generate output files, change the value of parameters and initial state values, etc. It is also in this environment that the end-user is defining the influent data (flow rate, concentration, etc.).

2.2 Cost module modification

The model in WEST® already contains a cost node, but for this particular case some modifications have to be made. The modifications will be described in detail for each cost implemented.

2.2.1 Taxes on nutrients in the effluent

Taxes on nutrients are calculated based on the load released in the effluent; equation (1.1) is used to calculate the instant cost.

$$\frac{DKK}{time} = Q_{effluent} * S_{nutrient,eff} * F_{taxes}$$

$Q_{effluent}$ = Effluent flow rate

$S_{nutient,eff}$ = Nutrient concentration in the effluent

F_{taxes} = Taxe cost on nutrients (1.1)

Equation (1.2) is used to calculate the cumulative cost over the simulation period:

$$\text{cumulative cost} = \int_{t_{init}}^{t_{fin}} \frac{DKK}{time} dt \quad (1.2)$$

All variables and parameters in the above equations have to be defined in the cost module. Effluent flow rate and nutrient concentrations are interface variables, which mean that their values will come from other units. Each nutrient needs its own variable, one for total nitrogen, one for total phosphorus and one for BOD_5. Cost factors are parameters, which mean that they are time independent and they are set by the end-user. The default values are the ones given by the Avedøre WWTP operators (see Table 2), but they can easily be changed in the experimentation environment. Again, one cost factor

has to be created for each nutrient. Moreover, for each nutrient, two states variables have to be created, one for the instant cost and one for the cumulative cost.

Table 2: Default values of cost factors for nutrients in the effluent (source: Avedøre WWTP)

Nutrient	default value of cost factor (DKK/kg)	Parameter name in WEST®
BOD_5	0.011	F_BOD5
Total nitrogen	0.020	F_TN
Total phosphorus	0.110	F_TP

When parameters, variables and equations are created in the model editor, some nodes have to be added to the model in the configuration builder to communicate data to the cost module. For this part, four sensors have to be added to the effluent line, one flow sensor and three sensors for nutrient concentrations (see Figure 4). They are subsequently linked to their respective variable in the cost module.

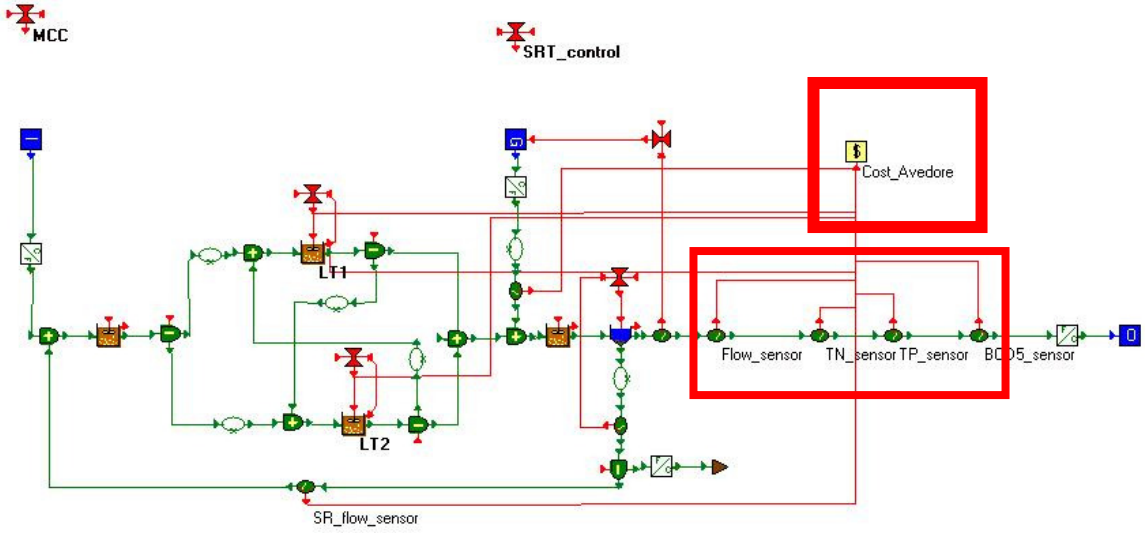


Figure 4: Model of the Avedøre WWTP after cost module implementation

2.2.2 Chemicals

The class of chemicals contains three different costs to evaluate: i) Cost of chemicals for phosphorus precipitation, ii) chemical cost for carbon addition and iii) the cost of handling additional inert sludge due to chemical precipitation of phosphorus.

Phosphorus precipitation

Costs of chemicals are basically the flow rate of chemicals added multiplied by the cost factor (equation (1.3)), giving the instant cost. For the cumulative cost, the costs are integrated over the simulation period (equation (1.4)).

$$\frac{DKK}{time} = Q_{chem,pp} * F_{chem,pp}$$

$Q_{chem,pp}$ = Flow rate of chemical for phosphorus precipitation

$F_{chem,pp}$ = Cost factor for chemical for phosphorus precipitation (1.3)

$$\text{cumulative cost} = \int_{t_{init}}^{t_{fin}} \frac{DKK}{time} dt \quad (1.4)$$

The model created in WEST® is based on the use of ferric hydroxide ($Fe(OH)_3$) to model the chemical precipitation of phosphorus. Before using those equations, some conversions have to be made since the product used at Avedøre WWTP is ferric chloride ($FeCl_3$). The commercial name of this product is JKL (see Annex B). Since the active agent in the reaction is the same (Fe^{3+}), the kinetic model does not need to be changed; only a density conversion is needed. The conversion is shown in equation (1.5). This equivalent density (324700 g/m^3) is entered directly as a parameter (MEAN(X_MEOH)) in the chemical dosage node. In the configuration builder, a flow sensor has to be put into the chemical dosage line and the signal of this sensor has to be linked to the cost module.

$$JKL \Rightarrow 170 \frac{g\ Fe^{3+}}{L}$$

$$\text{equivalent density of JKL as Fe(OH)}_3 = 170 \frac{g\ Fe^{3+}}{L} * 1.91 \frac{g\ Fe(OH)_3}{g\ Fe^{3+}} \quad (1.5)$$

$$\text{equivalent density of JKL as Fe(OH)}_3 = 324.7 \frac{g}{L} = 324\,700 \frac{g}{m^3}$$

Carbon addition

The steps to implement carbon addition cost calculation are the same as the ones for phosphorus precipitation. The current model in WEST® is based on the use of methanol or ethanol to model carbon addition. If the chemical used is different a conversion is needed. Equation (1.6) shows how the instant cost is calculated while equation (1.7) shows the cumulative cost over the simulation period. As for the phosphorus precipitation, only a flow sensor on the chemical line is needed.

$$\frac{DKK}{time} = Q_{chem,ca} * F_{chem,ca}$$

$Q_{chem,ca}$ = Flow rate of chemical for carbon addition

$F_{chem,ca}$ = Cost factor for chemical for carbon addition (1.6)

$$\text{cumulative cost} = \int_{t_{init}}^{t_{fin}} \frac{DKK}{time} dt \quad (1.7)$$

Chemical sludge

The last cost in this class is the cost for treating the additional sludge coming from the phosphorus precipitation. The approximate amount of additional dry sludge per kilogram of JKL added is 0.33 kg. This has to be multiplied by the density of JKL (1500 kg/m^3), resulting in a conversion factor of 495 kg of dry sludge per cubic meter of JKL. It is assumed that 1 kg of dry chemical sludge gives, after incineration, 1 kg of flyash. The disposal cost of flyash is 0.375 DKK per kg. Equations used for this cost are the following:

$$\frac{DKK}{time} = Q_{chem,pp} * F_{chem,s} * F_{flyash}$$

$Q_{chem,pp}$ = Flow rate of chemical for phosphorus precipitation

$F_{chem,s}$ = kg of sludge produced per kg of chemical

F_{flyash} = Disposal cost of flyash (1.8)

$$\text{cumulative cost} = \int_{t_{init}}^{t_{fin}} \frac{DKK}{time} dt$$

2.2.3 Energy

Two sources of energy consumption have been selected: aeration energy and pumping energy for the recycled activated sludge (RAS).

Pumping energy

The relation between pumping energy and flow rate depends on the efficiency of the pump, pipe length, water head, pumped liquid, etc. For this work, an empirical relation is used. Figure 5 shows the energy consumption as function of the RAS flow rate. The energy consumption shown includes pumping and mixing energy. The offset is

interpreted as constant energy consumption due to mixing and it will not be taken into account. The slope of the regression will be used as the conversion factor between RAS flow and pumping energy.

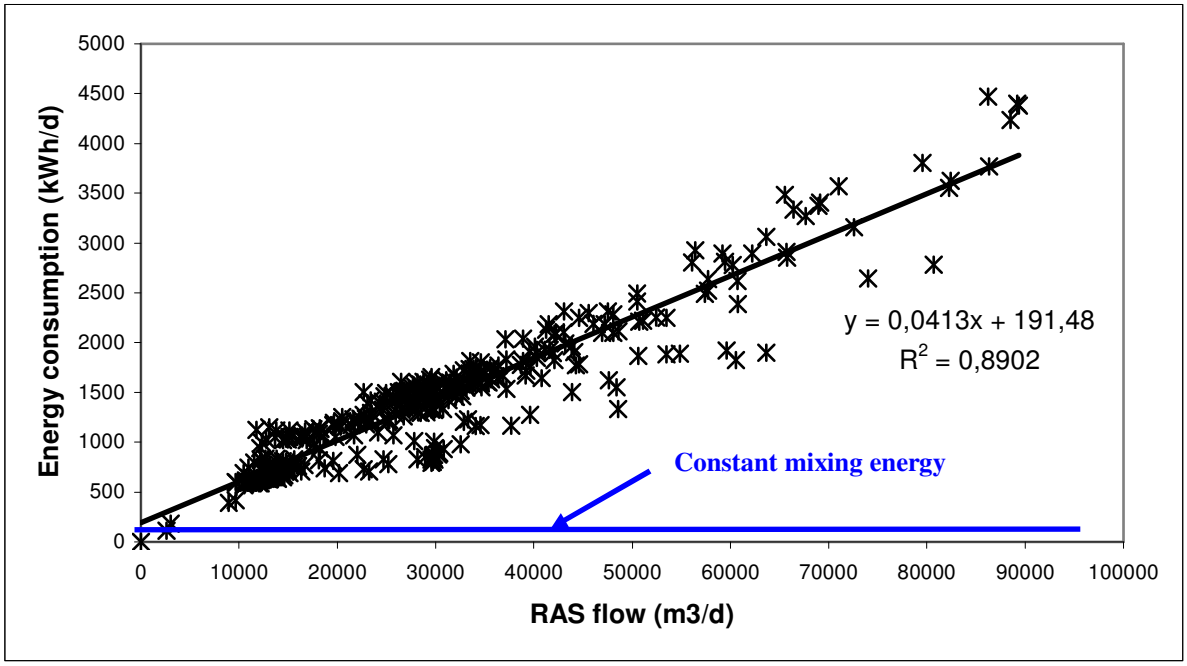


Figure 5: Energy consumption as function of the recycled activated sludge flow rate

To calculate the instant and the cumulative cost equations (1.9) are used:

$$\frac{energy}{time} = Q_{RAS} * F_{energy,flow}$$

Q_{RAS} =Returned activated sludge flow rate

$F_{energy,flow}$ =conversion between flow and pumping energy

(1.9)

$$\text{cumulative pumping energy} = \int_{t_{init}}^{t_{fin}} \frac{energy}{time} dt$$

For pumping energy estimation, the default value of the factor converting flow rate into energy (0.0413 kWh/m^3) had to be changed in the already existing WEST® model. In the configuration builder, only a flow sensor on the RAS line has been added, other information needed originates from units already present in the model.

Aeration energy

The aeration energy is also depending on a lot of factors specific to the WWTP: aeration equipment, altitude, wastewater composition, etc. The Avedøre WWTP is equipped with surface aerators (see Figure 6). For this type of aerators, the mass of transferred oxygen per kWh depends on the immersion depth of the aerator. At Avedøre WWTP the average immersion depth is 23 cm. With the graph provided by the manufacturer (Figure 7) it is possible to estimate the ratio between mass of transferred oxygen and energy consumption. As a default value in the model 1.85 kg O_2 per kWh will be used. Since the aeration control model in WEST® is providing an oxygen transfer rate (k_La), the k_La has to be transformed into an oxygen transfer rate and then into an energy consumption. The set of equations (1.10) is used to make this conversion.

$$\text{aeration energy}\left(kWh/d\right) = \frac{S_0^{sat}}{F_{AE} * 1000} * \int_{t_{int}}^{t_{fin}} \sum V * K_L a(t) dt$$

$$\text{where} \quad S_0^{sat} = 14.65 - 0.41 * T + 0.00798 * T^2 - 0.0000778 * T^3$$

S_0^{sat} = Oxygen saturation concentration

t = Time

F_{AE} = Aerator efficiency (1.10)

V = Tank volume

$K_L a$ = Oxygen tranfer rate

T = Temperature

The cumulative aeration energy cost is calculated by making an integral of the aeration energy (see equation (1.11)).

$$\text{cumulative aeration energy} = \int_{t_{init}}^{t_{fin}} \textit{aeration energy}\, dt \qquad (1.11)$$

Figure 6: Surface aerator used at Avedøre WWTP

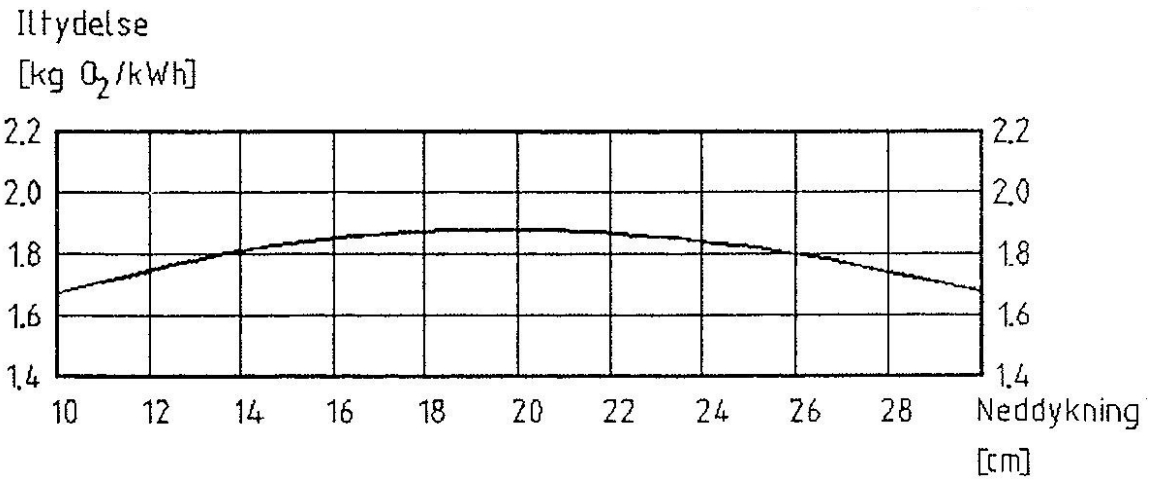


Figure 7: Mass of oxygen transferred as function of aerator depth (source: Krüger, see Annex C)

Since the model is made for one input and the Avedøre WWTP model has two aeration tanks, the aeration energy thus has two inputs. To this end a complete second set of variables and parameters was created to calculate the oxygen transfer based on the K_La. Two more variables have been created as well, one state variable for the oxygen saturation concentration (S_o^{sat}) and one interface variable for reactor temperature. The K_La is taken from the aeration controller and the temperature in the reactor is available from the reactor itself.

2.2.4 Energy cost as function of time

In Denmark, the energy cost is not fixed for industries; it varies depending on the time of day, the day of the week and the period of the year. The price chart for Avedøre is given in Table 3. However, after discussion with people from Avedøre WWTP, the decision was made to implement a simpler version (see Table 4) of the chart. In this version the price is only a function of the time of day. Note that the prices given in Table 4 also include taxes and distribution fees.

Table 3: Energy cost chart for Denmark (source: DongEnergy)

Period	Day	Time (h)	Price (DKK/kWh)
Period 1	Mon - Fri	0-6 and 21-24	0.115
	Sat, Sun and holidays, 1st May, 5th June, 24th and 31st Dec	Whole day	
Period 2	Oct – Mar Mon – Fri	6-8; 12-17; and 19-21	0.173
	Apr-Sep. Mon - Fri	6-8 and 12-21	
Period 3	Oct – Mar Mon - Fri	8-12 and 17-19	0.232
	Apr – Sep Mon – Fri	8-12	

Table 4: Simplified energy cost chart

Period	Time (h)	Price (DKK/kWh)
Period 1	0-6 and 21-24	0.502
Period 2	6-8 and 12-21	0.560
Period 3	8-12	0.619

Table 4 shows three different periods, but period one and two are divided into two periods. To reduce the cost calculation effort and to facilitate the use of the model for the end-user, the price chart has been implemented in a way so that only the end time of each period and the price have to be set (see Table 5). Finally, the parameter Start_time has been created to indicate at what time of day the simulation starts. The value must be between 0 and 24 hours.

Table 5: Tariff chart implemented in the cost module

Period	end Time (h)	Price (DKK/kWh)
Period 1	6	0.502
Period 2	8	0.560
Period 3	12	0.619
Period 4	21	0.560
Period 5	24	0.502

3. COST MODULE UTILISATION

The utilisation of the cost unit is quite simple, only a basic knowledge of WEST® is required. After the implementation, the end-user does not need to use the model editor nor in configuration builder; everything he needs is accessible in the experimentation environment. With a double-click on the cost module, called Cost_Avedore in the WEST® model of the plant (see Figure 8), a new window with different tabs appears. The first tab is called Info, and includes information about the unit, e.g. name of the model, the number of variables and parameters, etc.

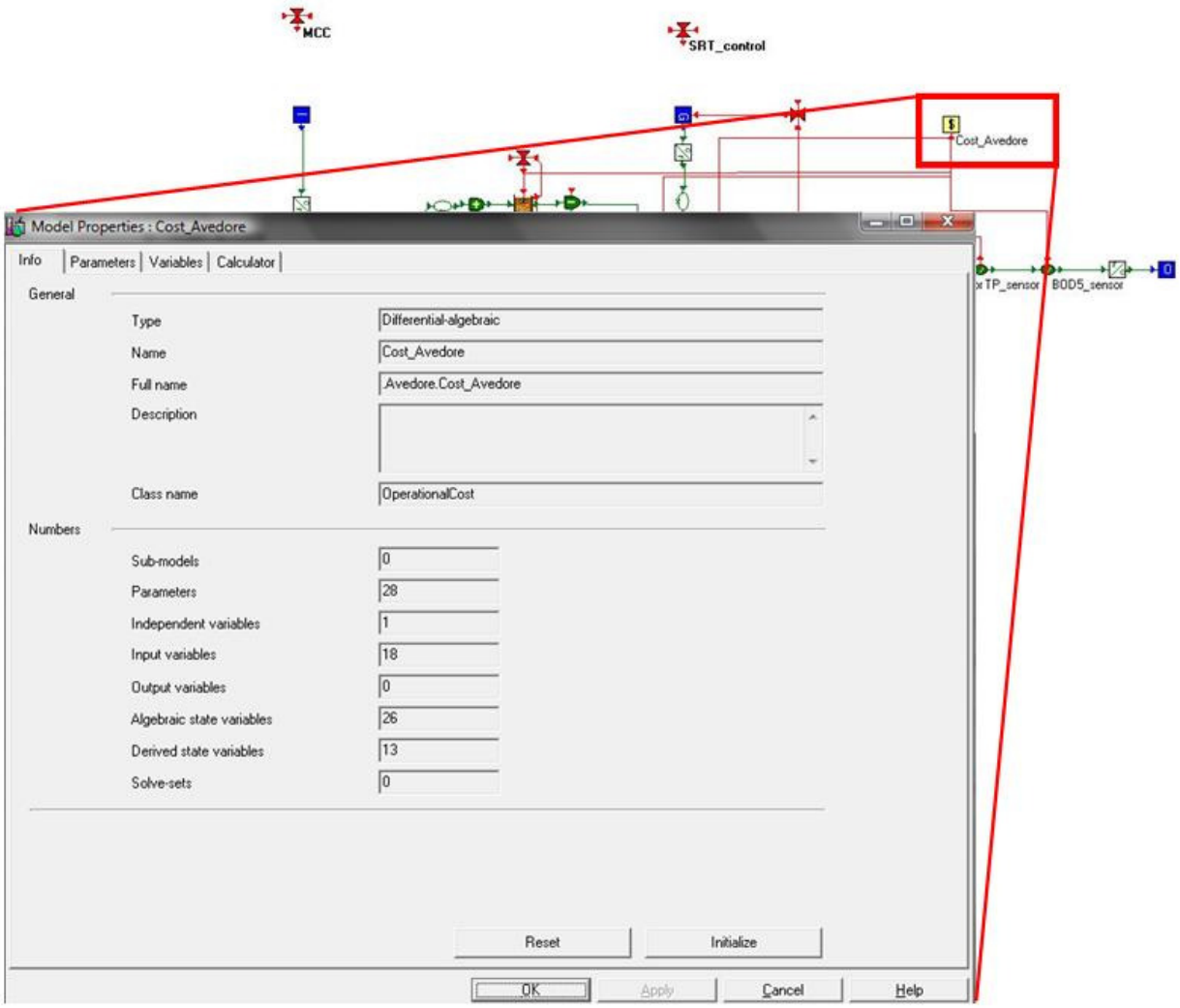
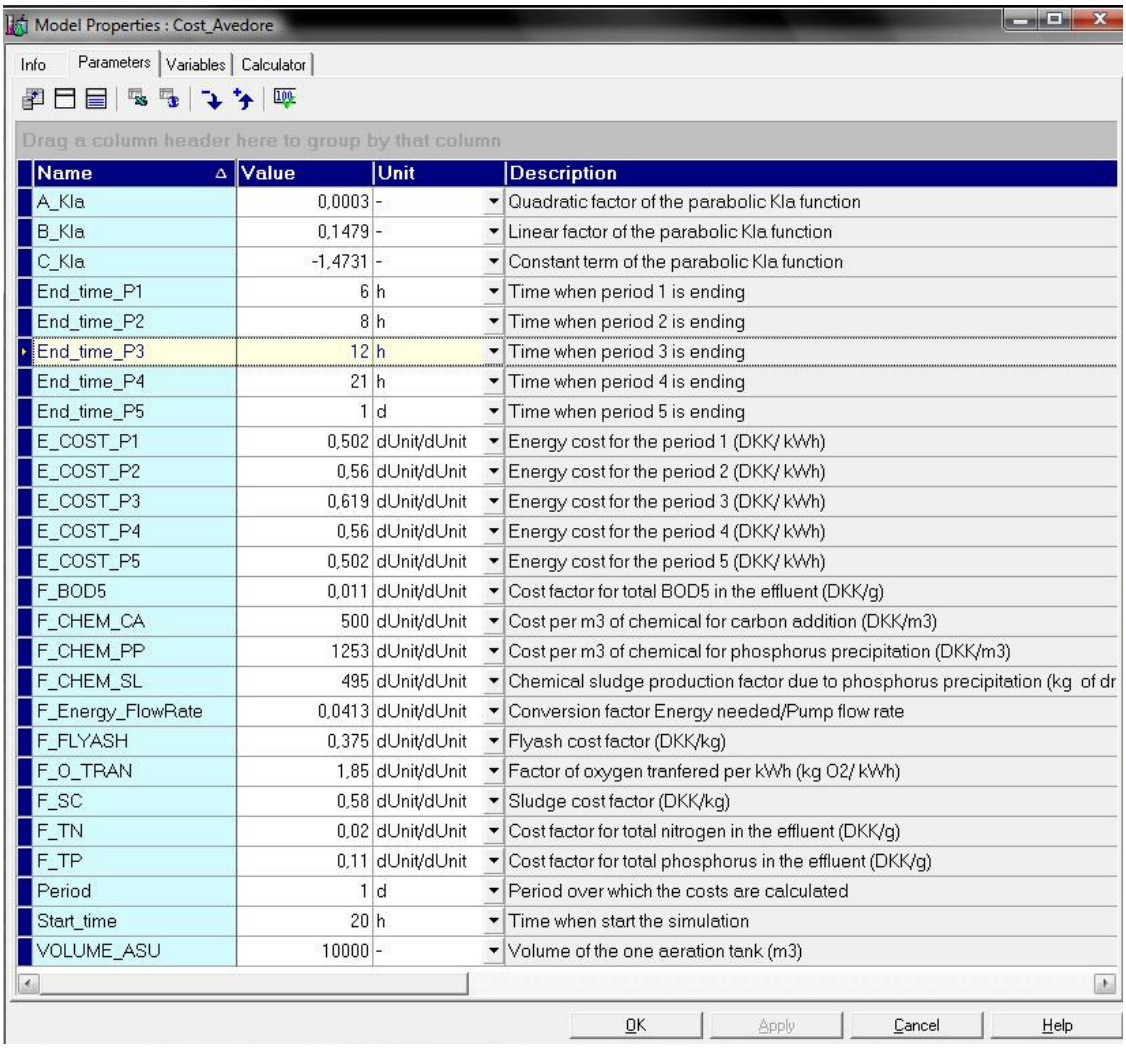


Figure 8: WEST® model of Avedøre WWTP

The second tab includes all parameters of the model. Parameter values can be changed and saved directly in this window. The name of the parameter, its value, its unit, its default value and a description of the parameters can be seen in this tab (see Figure 9).



Name	Value	Unit	Description
A_Kla	0,0003	-	Quadratic factor of the parabolic Kla function
B_Kla	0,1479	-	Linear factor of the parabolic Kla function
C_Kla	-1,4731	-	Constant term of the parabolic Kla function
End_time_P1	6	h	Time when period 1 is ending
End_time_P2	8	h	Time when period 2 is ending
End_time_P3	12	h	Time when period 3 is ending
End_time_P4	21	h	Time when period 4 is ending
End_time_P5	1	d	Time when period 5 is ending
E_COST_P1	0,502	dUnit/dUnit	Energy cost for the period 1 (DKK/ kWh)
E_COST_P2	0,56	dUnit/dUnit	Energy cost for the period 2 (DKK/ kWh)
E_COST_P3	0,619	dUnit/dUnit	Energy cost for the period 3 (DKK/ kWh)
E_COST_P4	0,56	dUnit/dUnit	Energy cost for the period 4 (DKK/ kWh)
E_COST_P5	0,502	dUnit/dUnit	Energy cost for the period 5 (DKK/ kWh)
F_BOD5	0,011	dUnit/dUnit	Cost factor for total BOD5 in the effluent (DKK/g)
F_CHEM_CA	500	dUnit/dUnit	Cost per m3 of chemical for carbon addition (DKK/m3)
F_CHEM_PP	1253	dUnit/dUnit	Cost per m3 of chemical for phosphorus precipitation (DKK/m3)
F_CHEM_SL	495	dUnit/dUnit	Chemical sludge production factor due to phosphorus precipitation (kg of dr
F_Energy_FlowRate	0,0413	dUnit/dUnit	Conversion factor Energy needed/Pump flow rate
F_FLYASH	0,375	dUnit/dUnit	Flyash cost factor (DKK/kg)
F_O_TRAN	1,85	dUnit/dUnit	Factor of oxygen tranfered per kWh (kg O2/ kWh)
F_SC	0,58	dUnit/dUnit	Sludge cost factor (DKK/kg)
F_TN	0,02	dUnit/dUnit	Cost factor for total nitrogen in the effluent (DKK/g)
F_TP	0,11	dUnit/dUnit	Cost factor for total phosphorus in the effluent (DKK/g)
Period	1	d	Period over which the costs are calculated
Start_time	20	h	Time when start the simulation
VOLUME_ASU	10000	-	Volume of the one aeration tank (m3)

Figure 9: Parameters of the cost module

The third tab shows all the results of the simulation. A column in this tab is named value, and is providing the results. Another column is named initial value. As for the

parameters' tab, the variable name, its unit and its description can be consulted (see Figure 10).

Special note: It is important before a simulation that all initial derived state values (second category) are set to zero (in red in Figure 10), otherwise the calculation will be erroneous.

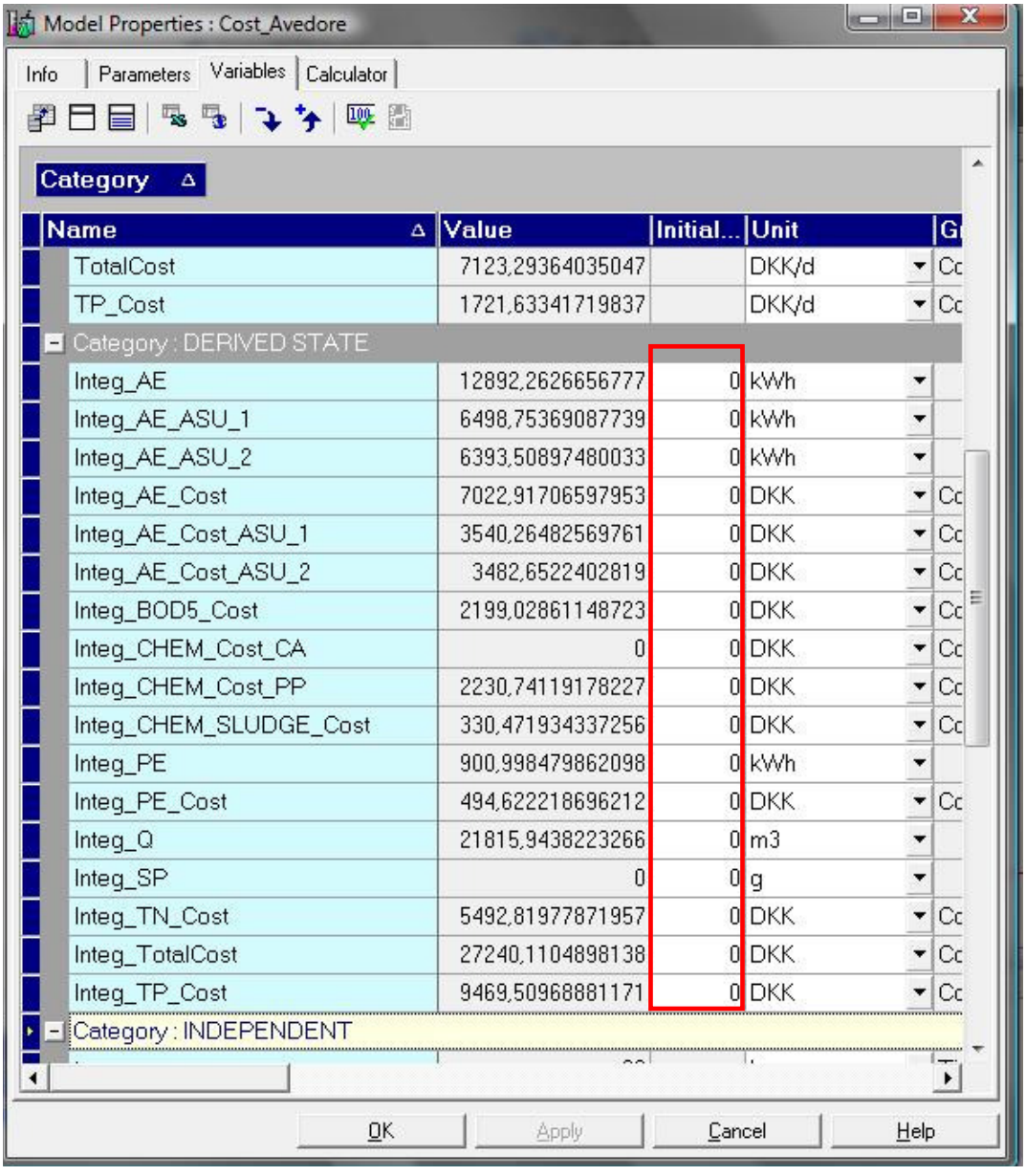


Figure 10: Variables of the cost module

The conversion factor between different currencies can be changed by opening the file named units.txt in the WEST directory. This directory is automatically created when WEST® is installed (typically in Programs\WEST\Bin). The third column of the Currency class corresponds to the conversion factor.

4. RESULTS AND DISCUSSION

In this section, cost estimations will be presented and discussed. To verify whether the Cost Module is working properly, simulations were run using a set of artificial input data created by Erik Lindblom. This data set is made for 100 days of simulation, but each day is subject to diurnal variation. That means that each day will give same results. Since the WEST® model is representing only one line of treatment, simulations have been run for one day and cost results have been multiplied by four to represent the whole plant. Table 6 is showing simulation results for each cost class. The aeration and pumping energy are shown in kWh per day rather than in DKK per day for two reasons. Firstly, the raw cost estimation given by the plant operators were in kWh per day. Hence this is the easiest way to compare the results and analyse the fit. Secondly, as seen before, the energy cost depends on the time of day. So, depending on the start time of the simulation the results would differ. By keeping them in kWh per day, they remain independent of the time of day. Results for the energy cost chart implementation will be shown later.

3.1 Taxes and chemicals

Table 6 shows the estimated variables, the units, raw estimations for one day of operation and estimations coming from the Cost Module.

Table 6: Cost module simulation results

Variables	units	Approximated cost (source: Avedøre WWTP)	Estimated by WEST® Cost Module
Total-N	DKK/d	6500	5493
Total-P		5000	9470
BOD_5		2300	2199
JKL		2500	2231
Chemical sludge			330
Aeration energy	kWh/d	14000	12892
Pumping energy		900	901

The first three lines in Table 6 show estimations for nutrient taxes. The total nitrogen and BOD_5 are well estimated, i.e. there is only a slight difference that is considered acceptable since the estimation from the plant operator are raw ones and the input data for the simulation is “artificial”.

For total phosphorus in the effluent, there is a significant difference between the raw estimation and the simulation, i.e. the estimation made by the cost module is nearly twice as high. Two reasons can explain this lack of fit: i) an overevaluation from the cost module or ii) a too high phosphorus concentration in the effluent. After a detailed look into the cost module, it was concluded that the problem is coming from the phosphorus removal model. In the present Avedøre WWTP model, the bio-P removal process is not described properly, thus the total phosphorus concentration in the effluent is too high.

To fit the chemical addition data, the set point of the chemical addition for the phosphorus precipitation model has been fixed to 0.7 mg/l. In reality the set point is 0.4

mg/l. Without changing the cost module, by fixing the problem of the bio-P removal model and by decreasing the set point of the controller to 0.4 mg/L, the estimation of the taxes on total-P in the effluent will be closer to the real cost.

There is no reference data available for the chemical sludge disposal cost, but it can be expected that this estimation is close to reality. The calculation of this cost is a direct function of the chemical dosage, which, as seen before, is well estimated and it is also a function of the factor giving the amount of flyash to treat per cubic meter of JKL added and the disposal cost for flyash. The disposal cost of flyash is a fixed parameter, so the only thing that could cause a poor fit is the conversion factor from JKL added for chemical sludge production.

3.2 Energy

The estimates of the aeration and pumping energy consumption by the cost module appear satisfying as they compare well to the raw estimations provided by the Avedøre WWTP staff. The tariff chart has been implemented and the results are the following:

RAS pumping cost for one day: 987 DKK
Aeration cost for one day: 7159 DKK

There is no data available about the daily cost of energy. To verify whether the model is running well, instant energy cost and time of day have been plotted as function of the simulation time (see Figure 11) to see whether the cost is changing over time and whether the time is properly separated in 24-hour periods. For this the start time has been set at 12h. The blue line represents the time of day and the red line the instant energy cost. This graph shows that the model is running properly.

Figure 11: Energy cost and time of day as function of simulation time

5. CONCLUSION

As part of a project that brings together Avedøre WWTP and Lund University, a WEST® model for the Avedøre WWTP has been developed by Erik Lindblom. model*EAU* joined this project to add a cost evaluation module to the existing plant model.

The first goal was to implement and calculate different costs grouped into three classes: i) Taxes on nutrients in the effluent, ii) costs for the addition of chemicals and iii) energy consumption costs. Concerning the taxes on nutrients, everything has been implemented and the module is running well. The taxes on phosphorus are not estimated well probably because of a problem in the biokinetic model. With an appropriate biological phosphorus removal model and the right set point of the controller (0.4 mg/L rather than 0.7) the taxes on phosphorus would give a better fit.

The second cost class was the dosage of chemicals, which includes chemical addition and chemical sludge treatment. The chemical addition is also providing a good estimation, but to reach this the set point of the controller must be set too high. However, as explained in the previous paragraph, with a bio-P model that works properly and a set point of 0.4 mg/L, the chemical dosage cost will still give a good estimation. The project was also asked to prepare the model for the use of different chemicals for phosphorus precipitation. As long as the active ion is Fe^{3+} the model will still give good estimates. The only thing to change is the conversion factor as shown in equation (1.5) to convert it into $Fe(OH)_3$. If the active ion is different from Fe^{3+}, the precipitation model has to be modified, but, importantly, the cost module remains the same.

The other cost evaluated in this class is the disposal cost of the additional inert sludge generated by the chemical phosphorus precipitation. There is no real data available for this cost, but since the only modelled variable used for this estimation is the chemical used and since this estimation is good, it can be expected that the cost for chemical sludge disposal is also good.

It was also requested to prepare the implementation with everything necessary to estimate carbon addition cost, all variables and parameters required are in the model, but since there are no carbon addition units in the Avedøre WWTP model, no results can be shown.

The last class was the energy cost, which includes aeration and RAS pumping energy. The comparison between real and estimated values is based on the energy consumption rather than on cost, because energy consumption is not affected by time which influences the energy cost chart. Again, estimations provided by the cost module are satisfying.

The last thing to implement in the model was the energy cost chart. For the time being the choice that was made consisted in implementing a simplified version of the real cost chart. Also, taxes and distribution fees were already included in the instant cost. This part of the modeling project is also working properly.

REFERENCES

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Nielsen, M.K. and Onnerth, T.B. (1995) Improvement of a Recirculating Plant by Introducing Star Control. Water Science and Technology 31(2), 171-180.

Henze, M., Gujer, W., Mino, T. and van Loosdrecht, M.C.M. (2000) Activated sludge models ASM1, ASM2, ASM2d and ASM3, IWA Publishing, London, UK.

DongEnergy
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ANNEX A MINUTES OF THE FIRST MEETING

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Skype: mathieu_beaupre

Hvidøvre, 071113

Description of work

Cost evaluation tool integrated with WEST simulations

Cost categories:

- power consumption
- chemicals consumption
- environmental taxes (effluent)
- added costs for chemical sludge production

Power consumption

- energy for
  - aeration based on simulated OUR and theoretical KLA curve assuming constant depth of submersion
  - RAS pumping based on a constant pumping energy per m^3

Chemicals consumption

- Different products for P-precipitation (JKL, PIX14, PAX,…), the conversion between WEST standard parameter and the actual product composition , the cost per unit of product in DKK or SEK
- Different products for carbon source dosage (methanol,..), + as above for P-precipitation

Environmental taxes

- establishing correlations for Avedøre and Damhusåen WWTPs, respectively, for effluent concentrations of BOD_5, Total N and Total P based on analytical records for COD, NH_4-N, NO_x-N, PO_4-P and SS
- develop conversions from WEST simulations to effluent BOD_5, TN and TP

Added costs for chemical sludge production

- based on an assumed cost for handling 1 kg of inert metal precipitates in the following sludge treatment and disposal, the change in costs as a direct function of changed product consumption for P-precipitation is included

RESULTS OF WORK

Input files for WEST will be the same as Erik's other input files – Mathieu will write accompanying descriptions.

WEST cost module calculations will be modified and adapted to the above categories of consumptions and costs per day.
Output of cost calculations will be presented as any other output variables from WEST including the options for exporting to, e.g., EXCEL spreadsheets.

The developed WEST cost module can be freely available for Lynetten, Avedøre, Lunds University and model*EAU*.

Input from SCA and RDA:

- Power Tariff Table
- KLA and power curve
- JKL product information cost and other chemicals from RDA
- Analytical data from RDA
- Taxation prices
- RAS pumping energy relations kWh/m^3
- Cost per kg of inert sludge produced

ANNEX B JKL SPECIFICATION

Kemwater™

JKL

Jern(III)kloridsulfatopløsning

Jern, trevalent – Fe^{3+}	11,5 ± 0,2 %	> 170 g/l JKL	*Normal 175 g/l JKL*
Jern, tovalent – Fe^{2+}	< 0,2 %	< 3 g/l JKL	
Klorid	~ 10,0 %	150 g/l JKL	
Sulfat	< 16,0 %	250 g/l JKL	

		Gennemsnit 2005 *mg/kg JKL*	Maxindhold *mg/kg JKL*	Gennemsnit 2005 *mg/kg Fe*	Maxindhold *mg/kg Fe*
Bly	**Pb**	0,8	5,0	6,9	44
Cadmium	**Cd**	< 0,03	< 0,05	< 0,26	0,44
Kobber	**Cu**	6,1	10	53	87
Krom	**Cr**	3,1	10	27	87
Kviksølv	**Hg**	< 0,003	0,05	< 0,03	0,44
Nikkel	**Ni**	26,4	30	230	261
Zink	**Zn**	64,1	200	557	1740

pH		< 0
Krystalisationstemperatur		0 ºC
Densitet		1,50 ton/ m^3
Viskositet ved 0 ºC		77 cP
(Brookfield spindle, LV nr. 1)	ved 23 ºC	22 cP
Aktiv substans		2,1 mol/kg
Leveringsform		Bulk, 800 /1000 l palletanke, 200 l tromler, 25 l dunke
Producent		Kemira Miljø A/S, Esbjerg

Denne tekniske information er kun vejledende

06-09 Kemira Miljø A/S PS 01.16

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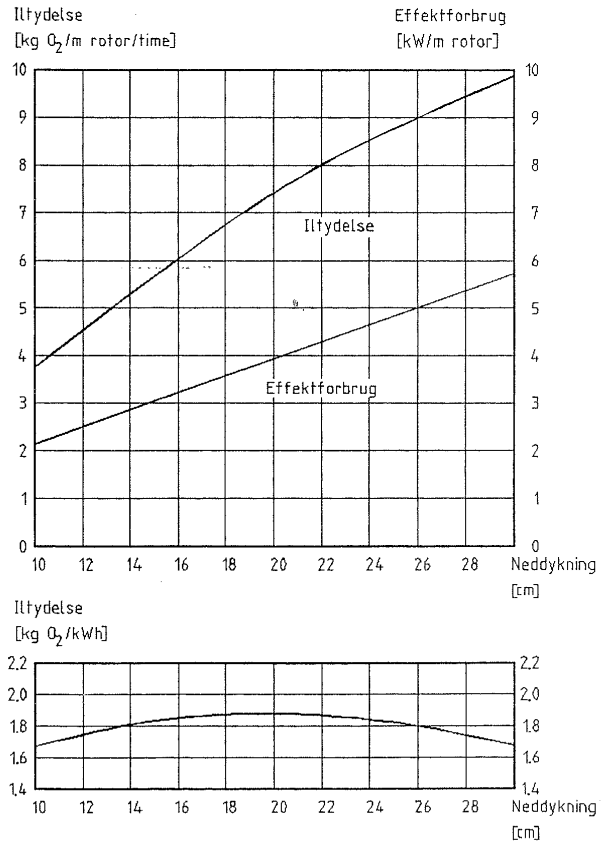
RENT VAND ER VORT LIV

ANNEX C SURFACE AERATOR SPECIFICATION

3 Karakteristikker

Diagram til bestemmelse af iltydelse og effektforbrug for Maxi-rotorer.

Iltydelsen er baseret på, at driften foregår under standardbetingelser i rent vand med en vanddybde på 3 m og en temperatur på 10°C, samt at rotoren er forsynet med ledeplader.



ANNEX D MSL CODE OF THE COST MODULE

```
       // ------------------------------------------------
// MOSTforWATER - Ghent University, BIOMATH, modelEAU
// implementation: Youri Amerlinck, Mathieu Beaupré, Peter Vanrolleghem
// Description: MSL-USER/WWTP/Base/Operational Cost
// ------------------------------------------------

#ifndef WWTP_BASE_EVALUATOR
#define WWTP_BASE_EVALUATOR

CLASS OperationalCost
  (* class = "cost" ; category = "default" *)
  "Calculation of the operational cost of the plant"

// References
// Copp, J.B. (1999). Respirometry in Control of the Activated Sludge Process.
// http://www.spb.wau.nl/mt/iawqstrproject (March 19, 1999).
//
// Debusscher, D. (1999). Een procedure voor evaluatie van op respirometrie
// gebaseerde controlestrategieën voor actiefslibsystemen. M.Sc. thesis, Gent,
// Faculty of Agricultural and Applied Biological Sciences, 125p.
//
// Debusscher, D., Vanhooren, H. and Vanrolleghem, P. (1999). Benchmarking two
// biomass loading control strategies for activated sludge WWTPs. Med. Fac.
// Landbouww. Univ. Gent, 64(5a), 127-132.

// Beaupré, M., Rieger, L., Vanrolleghem, P., Jeppson, U. (2008). Cost module
// implementation in the Avedore WWTP model. modelEAU, Université Laval,
// Québec, Canada, pp.


  SPECIALISES
  PhysicalDAEModelType :=
  {:
    interface <-
    {
     OBJ Kla_1 (* terminal = "in_1" *) "Kla" :
       OxygenTransferCoefficient := {: causality <- "CIN" ; group <-
"Measurement data" :};
     OBJ Q_Pump1 (* terminal = "in_1" *) "Q_Pump1" :
       FlowRate := {: causality <- "CIN" ; group <- "Measurement data" :};
     OBJ Q_Pump2 (* terminal = "in_1" *) "Q_Pump2" :
       FlowRate := {: causality <- "CIN" ; group <- "Measurement data" :};
     OBJ Q_Pump3 (* terminal = "in_1" *) "Q_Pump3" :
       FlowRate := {: causality <- "CIN" ; group <- "Measurement data" :};
     OBJ Q_Pump4 (* terminal = "in_1" *) "Q_Pump4" :
       FlowRate:= {: causality <- "CIN" ; group <- "Measurement data" :};
     OBJ Q_Pump5 (* terminal = "in_1" *) "Q_Pump5" :
       FlowRate := {: causality <- "CIN" ; group <- "Measurement data" :};
     OBJ Q_Pump_Waste1 (* terminal = "in_1" *) "Q_Pump6" :
       FlowRate := {: causality <- "CIN" ; group <- "Measurement data" :};
     OBJ Q_Pump_Waste2 (* terminal = "in_1" *) "Q_Pump7" :
       FlowRate := {: causality <- "CIN" ; group <- "Measurement data" :};
     OBJ TSS1 (* terminal = "in_1" *) "TSS1" :
       Concentration := {: causality <- "CIN" ; group <- "Measurement data" :};
     OBJ TSS2 (* terminal = "in_1" *) "TSS2" :
       Concentration := {: causality <- "CIN" ; group <- "Measurement data" :};
        OBJ Q_EFF (* terminal = "in_1" *) "Effluent flow rate" :
       FlowRate := {: causality <- "CIN" ; group <- "Measurement data" :};
```

```
// The following interface variables have been added by Mathieu Beaupré
// for the Avedore model

       // Total nitrogen concentration in the effluent

        OBJ N_TOT_EFF (* terminal = "in_1" *) "Total nitrogen in the effluent" :
       Concentration := {: causality <- "CIN" ; group <- "Measurement data" :};

       // Total phosphorus concentration in the effluent

        OBJ P_TOT_EFF (* terminal = "in_1" *) "Total phosphorus in the effluent"
:
       Concentration := {: causality <- "CIN" ; group <- "Measurement data" :};

       // BOD5 concentration in the effluent

        OBJ BOD5_EFF (* terminal = "in_1" *) "Total BOD5 in the effluent" :
       Concentration := {: causality <- "CIN" ; group <- "Measurement data" :};

       // Second Kla input for the second reactor

        OBJ Kla_2 (* terminal = "in_1" *) "Kla_2" :
       OxygenTransferCoefficient := {: causality <- "CIN" ; group <-
"Measurement data" :};

       // Flow of chemical dosage

        OBJ Q_CHEM_PP (* terminal = "in_1" *) "Flow of chemical for phosphorus
precipitation" :
       FlowRate := {: causality <- "CIN" ; group <- "Measurement data" :};
        OBJ Q_CHEM_CA (* terminal = "in_1" *) "Flow of chemical for carbon
addition" :
       FlowRate := {: causality <- "CIN" ; group <- "Measurement data" :};

       // Reactor temperature for the So_sat calculation

        OBJ T_ASU (* terminal = "in_1" *) "Temperature in the aeration tank" :
       CelsiusTemperature := {: causality <- "CIN" ; group <- "Measurement
data" :};
    };

    parameters <-
    {
    OBJ F_AC (* hidden = "1" *) "Aeration cost factor" : EnergyCostFactor := {:
value <- 0.173 ; group <- "Cost" :};
    OBJ F_PC (* hidden = "1" *) "Pumping cost factor" : EnergyCostFactor := {:
value <- 0.173 ; group <- "Cost" :};
    OBJ F_SC "Sludge cost factor" : CostPerMass := {: value <- 0.58 ; group <-
"Cost" :};
    OBJ A_Kla "Quadratic factor of the parabolic Kla function" : Real := {:
value <- 0.0003 ; group <- "Energy" :};
    OBJ B_Kla "Linear factor of the parabolic Kla function" : Real := {: value
<- 0.1479 ; group <- "Energy" :};
    OBJ C_Kla "Constant term of the parabolic Kla function" : Real := {: value
<- -1.4731 ; group <- "Energy" :};
    OBJ Period "Period over which the costs are calculated" : Time := {: value
<- 1 ; group <- "Miscellaneous":};
    OBJ F_Energy_FlowRate "Conversion factor Energy needed/Pump flow rate" :
PumpEfficiency := {: value <- 0.0413 ; group <- "Energy":};

// The following parameters have been added by Mathieu Beaupré

   // Cost factor for nutrients and chemicals
```

```
      OBJ F_TN "Cost factor for total nitrogen in the effluent" : CostPerMass
:= {: value <- 0.020 ; group <- "Cost":};
      OBJ F_TP "Cost factor for total phosphorus in the effluent" : CostPerMass
:= {: value <- 0.110 ; group <- "Cost":};
      OBJ F_BOD5 "Cost factor for total BOD5 in the effluent" : CostPerMass :=
{: value <- 0.011 ; group <- "Cost":};
    OBJ F_CHEM_PP "Cost per m3 of chemical for phosphorus precipitation" :
CostPerVolume := {: value <-1253 ; group <- "Cost":};
      OBJ F_CHEM_CA "Cost per m3 of chemical for carbon addition" :
CostPerVolume := {: value <- 500 ; group <- "Cost":};
      OBJ F_CHEM_SL "Chemical sludge production factor due to phosphorus
precipitation" : Concentration := {: value <- 495 ; group <- "Cost":};
      OBJ F_FLYASH "Flyash cost factor" : CostPerMass := {: value <- 0.375 ;
group <- "Cost":};

   // Oxygen transfer efficiency of the aerator

      OBJ F_O_TRAN "Oxygen transfer efficiency of the aerator" :
AeratorEfficiency := {: value <- 1850 ; group <- "Energy":};

   // Aeration tank volume

      OBJ VOLUME_ASU "Volume of the one aeration tank" : Volume := {: value <-
10000 ; group <- "Volume":};

   // Cost of energy for each period during the day

      OBJ E_COST_P1 "Energy cost for period 1" : EnergyCostFactor := {: value
<- 0.502 ; group <- "Cost":};
      OBJ E_COST_P2 "Energy cost for period 2" : EnergyCostFactor := {: value
<- 0.560 ; group <- "Cost":};
      OBJ E_COST_P3 "Energy cost for period 3" : EnergyCostFactor := {: value
<- 0.619 ; group <- "Cost":};
      OBJ E_COST_P4 "Energy cost for period 4" : EnergyCostFactor := {: value
<- 0.560 ; group <- "Cost":};
      OBJ E_COST_P5 "Energy cost for period 5" : EnergyCostFactor := {: value
<- 0.502 ; group <- "Cost":};

   // End time of each period

      OBJ End_time_P1 "End time of period 1" : Time := {: value <- 0.25 ; group
<- "Time":};
      OBJ End_time_P2 "End time of period 2" : Time := {: value <- 0.3333333333
; group <- "Time":};
      OBJ End_time_P3 "End time of period 3" : Time := {: value <- 0.5 ; group
<- "Time":};
      OBJ End_time_P4 "End time of period 4" : Time := {: value <- 0.875 ;
group <- "Time":};
      OBJ End_time_P5 "End time of period 5" : Time := {: value <- 1 ; group <-
"Time":};

   // Actual time of the day of the first time instant of the simulation

      OBJ Start_time "Time when start the simulation " : Time := {: value <- 0
; group <- "Time":};

      };

    independent <-
    {
    OBJ t "Time" : Time := {: group <- "Time" :};
    };
```

```
    state <-
     {
    OBJ AE "Aeration energy" : EnergyFlow := {: group <- "Energy" :};
    OBJ Integ_AE "Integral of aeration energy" : ElectricalEnergy ;
    OBJ PE "Pumping energy" : EnergyFlow := {: group <- "Energy" :};
    OBJ Integ_PE "Integral of Pumping Energy" : ElectricalEnergy ;
       OBJ Integ_Q "Integral of Pumping flow" : Volume ;
    OBJ SludgeProduction "Sludge production" : MassFlow := {: group <- "Sludge"
:};
    OBJ Integ_SP "Integral of sludge production" : Mass ;
    OBJ AE_Cost "Aeration cost" : InstantCost := {: group <- "Cost" :};
       OBJ Integ_AE_Cost "Integral of aeration cost" : Danish := {: group <-
"Cost" :};
    OBJ PE_Cost "Pumping cost" : InstantCost := {: group <- "Cost" :};
       OBJ Integ_PE_Cost "Integral of Pumping cost" : Danish := {: group <-
"Cost" :};
    OBJ SludgeCost "Sludge cost" : InstantCost := {: group <- "Cost" :};
    OBJ TotalCost "Total cost" : InstantCost := {: group <- "Cost" :};
       OBJ Integ_TotalCost "Integral of Total cost" : Danish := {: group <-
"Cost" :};


// The following state variables have been added by Mathieu Beaupré
// for the Avedore model

   // Instant cost of nutrients in the effluent

       OBJ TN_Cost "Instant cost of the nitrogen in the effluent" : InstantCost
:= {: group <- "Cost" :};
       OBJ TP_Cost "Instant cost of the phosphorus in the effluent" :
InstantCost := {: group <- "Cost" :};
       OBJ BOD5_Cost "Instant cost of BOD5in the effluent" : InstantCost := {:
group <- "Cost" :};

   // Cumulative cost of nutrient in the effluent

    OBJ Integ_TN_Cost "Cumulative cost of total nitrogen in the effluent" :
Danish := {: group <- "Cost" :};
    OBJ Integ_TP_Cost "Cumulative cost of total phosphorus in the effluent" :
Danish := {: group <- "Cost" :};
    OBJ Integ_BOD5_Cost "Cumulative cost of the BOD5 in the effluent" : Danish
:= {: group <- "Cost" :};


   // Instant cost of chemical dosage

       OBJ CHEM_Cost_PP "Instant cost of chemical addition for phosphorus
precipitation" : InstantCost := {: group <- "Cost" :};
       OBJ CHEM_Cost_CA "Instant cost of chemical addition for carbon addition"
: InstantCost := {: group <- "Cost" :};

   // Cumulative cost of chemical dosage

    OBJ Integ_CHEM_Cost_PP "Cumulative cost of chemical addition for phosphorus
precipitation" : Danish := {: group <- "Cost" :};
       OBJ Integ_CHEM_Cost_CA "Cumulative cost of chemical addition for carbon
addition" : Danish := {: group <- "Cost" :};

   // Chemical sludge treatment cost

    OBJ CHEM_SLUDGE_Cost "Instant chemical sludge treatment cost" : InstantCost
:= {: group <- "Cost" :};
```

```
      OBJ Integ_CHEM_SLUDGE_Cost "Chemical sludge treatment cumulative cost" :
Danish := {: group <- "Cost" :};

   // Oxygen saturation concentration

      OBJ S_O_SAT "Oxygen saturation concentration" : Concentration := {: group
<- "Concentration" :};

   // Aeration energy and cost for reactor 1

      OBJ AE_ASU_1 "Aeration energy 1" : EnergyFlow := {: group <- "Energy" :};
      OBJ Integ_AE_ASU_1 "Integral aeration energy 1" : ElectricalEnergy ;
      OBJ AE_Cost_ASU_1 "Aeration cost 1" : InstantCost := {: group <- "Cost"
:};
      OBJ Integ_AE_Cost_ASU_1 "Integral of aeration cost 1" : Danish := {:
group <- "Cost" :};

   // Aeration ennergy and cost for reactor 2

      OBJ AE_ASU_2 "Aeration energy 2" : EnergyFlow := {: group <- "Energy" :};
      OBJ Integ_AE_ASU_2 "Integral aeration energy 2" : ElectricalEnergy ;
      OBJ AE_Cost_ASU_2 "Aeration cost 2" : InstantCost := {: group <- "Cost"
:};
      OBJ Integ_AE_Cost_ASU_2 "Integral of aeration cost 2" : Danish := {:
group <- "Cost" :};


   // Time of the day

      OBJ Day_time "Time of the day" : Time := {: group <- "Time" :};

   // Instant energy cost

      OBJ Instant_Energy_Cost "Instant Energy Cost" : InstantCost := {: group
<- "Cost" :};



       };

    equations <-
    {

      // this equation is calculating the time of the day

      state.Day_time = ((parameters.Start_time + independent.t) -
floor(parameters.Start_time + independent.t));


   // Calculation for saturation concentration of oxygen

    state.S_O_SAT = 14.65 + interface.T_ASU *(-0.41 + interface.T_ASU *
(0.00799 - 0.0000778 * interface.T_ASU));

   // The following equations have been modified to keep the energy contant
   // when the Kla is negative

    state.AE_ASU_1 = IF (interface.Kla_1 > 0)
                         THEN parameters.VOLUME_ASU * interface.Kla_1 *
state.S_O_SAT / parameters.F_O_TRAN
                         ELSE 0;
```

```
      state.AE_ASU_2 = IF (interface.Kla_2 > 0)
                       THEN parameters.VOLUME_ASU * interface.Kla_2 *
state.S_O_SAT / parameters.F_O_TRAN
                       ELSE 0;


   // Cumulative aeration energy


    DERIV(state.Integ_AE_ASU_1,[independent.t])= state.AE_ASU_1;
      DERIV(state.Integ_AE_ASU_2,[independent.t])= state.AE_ASU_2;

      state.AE = state.AE_ASU_1 + state.AE_ASU_2;
      DERIV(state.Integ_AE, [independent.t]) = state.AE;


   // Aeration cost in function of the period of the day

      state.AE_Cost_ASU_1 = IF ( state.Day_time < parameters.End_time_P1)
                       THEN state.AE_ASU_1 * parameters.E_COST_P1
                       ELSE IF ( state.Day_time < parameters.End_time_P2)
                       THEN state.AE_ASU_1 * parameters.E_COST_P2
                       ELSE IF ( state.Day_time < parameters.End_time_P3)
                       THEN state.AE_ASU_1 * parameters.E_COST_P3
                       ELSE IF ( state.Day_time < parameters.End_time_P4)
                       THEN state.AE_ASU_1 * parameters.E_COST_P4
                       ELSE state.AE_ASU_1 * parameters.E_COST_P5;

    DERIV(state.Integ_AE_Cost_ASU_1, [independent.t]) = state.AE_Cost_ASU_1;

      state.AE_Cost_ASU_2 = IF ( state.Day_time < parameters.End_time_P1)
                       THEN state.AE_ASU_2 * parameters.E_COST_P1
                       ELSE IF ( state.Day_time < parameters.End_time_P2)
                       THEN state.AE_ASU_2 * parameters.E_COST_P2
                       ELSE IF ( state.Day_time < parameters.End_time_P3)
                       THEN state.AE_ASU_2 * parameters.E_COST_P3
                       ELSE IF ( state.Day_time < parameters.End_time_P4)
                       THEN state.AE_ASU_2 * parameters.E_COST_P4
                       ELSE state.AE_ASU_2 * parameters.E_COST_P5;

      DERIV(state.Integ_AE_Cost_ASU_2, [independent.t]) = state.AE_Cost_ASU_2;

      state.AE_Cost = state.AE_Cost_ASU_1 + state.AE_Cost_ASU_2;
      DERIV(state.Integ_AE_Cost, [independent.t]) = state.AE_Cost;


   //Instant energy cost

      state.Instant_Energy_Cost = IF ( state.Day_time < parameters.End_time_P1)
                       THEN parameters.E_COST_P1
                       ELSE IF ( state.Day_time < parameters.End_time_P2)
                       THEN parameters.E_COST_P2
                       ELSE IF ( state.Day_time < parameters.End_time_P3)
                       THEN parameters.E_COST_P3
                       ELSE IF ( state.Day_time < parameters.End_time_P4)
                       THEN parameters.E_COST_P4
                       ELSE parameters.E_COST_P5;



      DERIV(state.Integ_Q,[independent.t])= interface.Q_Pump1+
interface.Q_Pump2 + interface.Q_Pump3 + interface.Q_Pump4 + interface.Q_Pump5 +
```

```
interface.Q_Pump_Waste1 + interface.Q_Pump_Waste2;

      state.PE = parameters.F_Energy_FlowRate * (interface.Q_Pump1+
interface.Q_Pump2 + interface.Q_Pump3 + interface.Q_Pump4 + interface.Q_Pump5 +
interface.Q_Pump_Waste1 + interface.Q_Pump_Waste2) ;
      DERIV(state.Integ_PE,[independent.t]) = state.PE;

      state.PE_Cost = IF ( state.Day_time < parameters.End_time_P1)
                          THEN state.PE * parameters.E_COST_P1
                          ELSE IF ( state.Day_time < parameters.End_time_P2)
                          THEN state.PE * parameters.E_COST_P2
                          ELSE IF ( state.Day_time < parameters.End_time_P3)
                          THEN state.PE * parameters.E_COST_P3
                          ELSE IF ( state.Day_time < parameters.End_time_P4)
                          THEN state.PE * parameters.E_COST_P4
                          ELSE state.PE * parameters.E_COST_P5;

    DERIV(state.Integ_PE_Cost,[independent.t])= state.PE_Cost;

      DERIV(state.Integ_SP,[independent.t])= interface.TSS1 *
interface.Q_Pump_Waste1 + interface.TSS2 * interface.Q_Pump_Waste2;
      state.SludgeProduction = state.Integ_SP ;


      state.SludgeCost = state.SludgeProduction * parameters.F_SC / 1000.0;


   // Instant and cumulative cost for the chemical dosage and nutrients in the
   // effluent

      state.TN_Cost = interface.Q_EFF * interface.N_TOT_EFF * parameters.F_TN ;
      DERIV(state.Integ_TN_Cost,[independent.t])= state.TN_Cost;

      state.TP_Cost = interface.Q_EFF * interface.P_TOT_EFF * parameters.F_TP ;
      DERIV(state.Integ_TP_Cost,[independent.t])= state.TP_Cost;

      state.BOD5_Cost = interface.Q_EFF * interface.BOD5_EFF *
parameters.F_BOD5 ;
      DERIV(state.Integ_BOD5_Cost,[independent.t])= state.BOD5_Cost;

      state.CHEM_Cost_PP = interface.Q_CHEM_PP * parameters.F_CHEM_PP ;
      DERIV(state.Integ_CHEM_Cost_PP,[independent.t])= state.CHEM_Cost_PP;

      state.CHEM_Cost_CA = interface.Q_CHEM_CA * parameters.F_CHEM_CA ;
      DERIV(state.Integ_CHEM_Cost_CA,[independent.t])= state.CHEM_Cost_CA;

   // Chemical sludge coming from phosphorus precipitation
    state.CHEM_SLUDGE_Cost = interface.Q_CHEM_PP * parameters.F_CHEM_SL *
parameters.F_FLYASH ;
      DERIV(state.Integ_CHEM_SLUDGE_Cost,[independent.t])=
state.CHEM_SLUDGE_Cost;

   /// Total cost
   state.TotalCost = state.AE_Cost + state.PE_Cost + state.TN_Cost +
state.TP_Cost + state.BOD5_Cost + state.CHEM_Cost_PP + state.CHEM_Cost_CA +
state.CHEM_SLUDGE_Cost;
   DERIV(state.Integ_TotalCost,[independent.t])= state.TotalCost;

    };
  :};


#endif // WWTP_BASE_EVALUATOR
```