Approach for an integrated assessment and optimisation of waste water treatment and sediment remediation processes

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> > von Eduardo Federico Arévalo Saade aus San Salvador, El Salvador 2005

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Hamburg, February 25th 2006

Eduardo Arévalo

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### Abbreviations

AETAquatic ecotoxicity potentialAOXAdsorbable halogenated organicsBCTBacteria contact test with bacillus cereus as test organismBDDBoron doped diamond anodesBTPBest theoretical performance of a processBUWALSwiss Federal Agency of Environment, Forestry and LandscapeCODChemical oxygen demandDBTDibutyltinDSADimensionally stable anodesDOCDissolved organic carbonEIAEnvironmental impact assessmentERAEcological risk assessmentEUSESEuropean union system for evaluation of substancesFUFunctional unit in life-cycle assessmentGACGranular activated carbonLBTLife-cycle inventoryLCALife-cycle inventoryLCILife-cycle inventoryLCILife-cycle inventoryLCILife-cycle inventoryLPIntegrated product policy of the EUIPPCIntegrated product policy of the EUIPPCIntegrated product policy of the EUIPPCIntegrated product policy of the EUIPPCNon-linear programmingMADAMulti-attribute decision analysisMBTMonobutyltinNLPOrganotin speciesREACHPolicy for the registration, evaluation and authorisation of chemicals of the European UnionSED-TOXSediment coxicity potentialSHEStandard hydrogen electordeSOSingle objective optimisationTHEStandard hydrogen electordeSO	AGI	Algae growth inhibition test with Pseudokirchneriella subcapitata
AOXAdsorbable halogenated organicsBCTBacteria contact test with bacillus cereus as test organismBDDBoron doped diamond anodesBTPBest theoretical performance of a processBUWALSwiss Federal Agency of Environment, Forestry and LandscapeCODChemical oxygen demandDBTDibutyltinDSADimensionally stable anodesDOCDissolved organic carbonEIAEnvironmental impact assessmentERAEcological risk assessmentEUSESEuropean union system for evaluation of substancesFUFunctional unit in life-cycle assessmentGACGranular activated carbonLBTLuminescence bacteria test with Vibrio fischeriLCALife-cycle costingLCIALife-cycle inventoryLCIALife-cycle inventoryLCIALife-cycle impact assessmentLPLinear programmingHTHuman toxicityIPPCIntegrated pollution prevention and controlMOAMulti-attribute decision analysisMBTMonobutyltinNLPNon-linear programmingOTOrganotin speciesREACHPolicy for the registration, evaluation and authorisation of chemicals of the European UnionSED-TOXSediment toxicity potentialSHEStandard hydrogen electrodeSOSingle objective optimisationTLPStandard colority potentialSHEStandard hydrogen electrodeSOSingle objective optimisation	AET	
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IPPCIntegrated pollution prevention and controlMOMultiobjective optimisationMADAMulti-attribute decision analysisMBTMonobutyltinNLPNon-linear programmingOTOrganotin speciesREACHPolicy for the registration, evaluation and authorisation of chemicals of the European UnionSED-TOXSediment toxicity indexSETSediment ecotoxicity potentialSNPSingle objective optimisationTBTTributyltin	HT	Human toxicity
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SED-TOXSediment toxicity indexSETSediment ecotoxicity potentialSHEStandard hydrogen electrodeSOSingle objective optimisationTBTTributyltin	REACH	Policy for the registration, evaluation and authorisation of chemicals of
SETSediment ecotoxicity potentialSHEStandard hydrogen electrodeSOSingle objective optimisationTBTTributyltin		the European Union
SHEStandard hydrogen electrodeSOSingle objective optimisationTBTTributyltin	SED-TOX	Sediment toxicity index
SOSingle objective optimisationTBTTributyltin	SET	Sediment ecotoxicity potential
TBT Tributyltin	SHE	Standard hydrogen electrode
-	SO	Single objective optimisation
Ti/IrO <sub>2</sub> Titanium coated with Iridium dioxide anodes	TBT	Tributyltin
	Ti/IrO <sub>2</sub>	Titanium coated with Iridium dioxide anodes

# USES-LCA Uniform system for evaluation of substances for impact assessment in life-cycle assessment

### List of symbols

а	Weighting factor for treatment costs
А	Acidification potential effects, kg SO <sub>2</sub> eq./m <sup>3</sup> , kg SO <sub>2</sub> eq./t
A <sub>Anode</sub>	Anodic area installed in an electrolysis cell, cm <sup>2</sup>
A <sub>lab</sub> , A <sub>scale-up</sub>	Anodic area installed in the electrolysis cell at laboratory scale and at
× ×	large scale (10 m <sup>3</sup> /h)
BV	Bed volumes to treat before regenerating the activated carbon bed
Ci	Cost of piece of equipment i (e.g. pumps, stirrers, vessels, etc.), €
C <sub>AOX</sub>	AOX concentration, mg/L, mg/kg
C <sub>Anode</sub>	Price of the anode material, $\epsilon/m^2$
CAPT	Cumulative average of phase toxicity (SED-TOX methodology)
C <sub>NaCl</sub>	Cost of NaCl, €/kg
$C_{TBT}, C_{DBT}$	Concentration of TBT and DBT, ng/L
CI <sub>El</sub>	Capital investment, €
d	Depreciation period, a
D	Function describing the distance between the normalised Pareto front
	and the reference point in the distance-to-reference-point theory
DAR	Depletion of abiotic resources effects, MJ fossil energy/m <sup>3</sup> ,
	MJ fossil energy/t
E	Electricity consumption, kWh/m <sup>3</sup> , kWh/t
EBCT	Empty bed contact time of the activated carbon column, h
$EC_{El}$	Costs of electricity for the electrolysis, $\epsilon/m^3$ , $\epsilon/t$
$EC_{Equipment}$	Costs of electricity to run the equipment of the process, $\epsilon/m^3$ , $\epsilon/t$
GW	Global warming effects, kg CO <sub>2</sub> eq./m <sup>3</sup> , kg CO <sub>2</sub> eq./t
i	Current density applied in electrochemical treatment, mA/cm <sup>2</sup>
I <sub>AGI-G4</sub>	Inhibition of dilution step G4 for algae growth inhibition test, %
I <sub>LBT-G4</sub>	Inhibition of dilution step G4 for luminescence bacteria test, %
IC	Investment costs, $\epsilon/m^3$ , $\epsilon/t$
IC <sub>BDD</sub> , IC <sub>Ti/IrO2</sub>	Investment costs for electrochemical treatment using BDD or Ti/IrO <sub>2</sub> anodes, €/m <sup>3</sup>
IC	Investment costs for flocculation, $\epsilon/m^3$
IC <sub>Floc</sub> IC <sub>GAC</sub>	Investment costs for flocculation, $\epsilon/m$ Investment costs for granular activated carbon adsorption, $\epsilon/m^3$
$TC_{GAC}$ $TC_{Floc1}$ , $TC_{Floc2}$	Treatment costs of flocculation for process chains 1 and 2, $\epsilon/m^3$
110017 11002	Investment costs of the electrochemical treatment, $\epsilon/m^3$
IC <sub>E1</sub>	investment costs for the electrochemical treatment, t/m

M <sub>k</sub>	Distance between the normalised Pareto front and the reference point in
	the distance-to-reference-point methodology
$M_{Added\_NaCl}$	Mass of NaCl added to the sediment suspension, kg/t
MC	Material costs for the pilot plant to treat TBT contaminated sediments,
	€/t
n	Number of tests of a bioassay battery indicating a toxic response (SED-
	TOX methodology)
n <sub>i</sub>	Quantity of pieces of equipment i required (i.e. pumps, cells, vessels)
norm_obj <sub>i</sub>	Normalised value of objective i
norm_LCA	Normalised value of LCA indicators (DAR, GW, A)
$norm\_LCA_{min}$	Normalised minimum LCA indicators (norm_LCA <sub>min</sub> = 1)
norm_TC	Normalised treatment costs
$norm\_TC_{min}$	Normalised minimum treatment costs (norm_ $TC_{min} = 1$ )
$OC_{El}$	Operation costs, $\epsilon/m^3$ , $\epsilon/t$
$OC_{Floc1}, OC_{Floc2}$	Operation costs of flocculation with process chains 1 and 2, $\epsilon/m^3$
$OC_{BDD}, OC_{Ti/IrO2}$	Operation costs of electrochemical treatment using BDD or Ti/IrO_2 $$
	anodes, $\epsilon/m^3$
OC <sub>GAC</sub>	Operation costs of granular activated carbon adsorption, $\epsilon/m^3$
Q	Volumetric flow, m <sup>3</sup> /h
r	Redundancy factor (SED-TOX methodology)
r <sub>i</sub>	Coordinate of the reference point for objective i (Best performance
	point)
TC	Treatment costs, $\epsilon/m^3$ , $\epsilon/t$
$TC_{BDD}, TC_{Ti/IrO2}$	Treatment costs of electrochemical treatment using BDD or Ti/IrO <sub>2</sub> anodes, €/m <sup>3</sup>
TC <sub>GAC</sub>	Treatment costs of granular activated carbon adsorption, $\epsilon/m^3$
TIF	Toxicity incremental factor (SED-TOX methodology)
TU	Toxic units (SED-TOX methodology)
U	Working potential of the electrolysis cell, V
V <sub>Treated</sub>	Volume of water treated in the activated carbon filter before
reated	regeneration of the adsorber is needed, m <sup>3</sup>
$V_{Bed}$	Volume of the activated carbon bed, m <sup>3</sup>
V <sub>w</sub>	Batch volume of electrochemical treatment experiments, m <sup>3</sup>
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### Greek symbols

α	Exponent factor defining the form of the function for calculating the dis-
	tance to the reference point
τ	Residence time, h

## Summary

The aim of this work is the design, implementation and evaluation of an approach that integrates economic and environmental criteria for the assessment and optimisation of processes. Even it is clear that the paradigm of sustainable development is the guiding principle to evaluate processes and any human activity, the approach designed covers only two of the columns of the concept of sustainability: economy and environment. The inclusion of social or socio-economic criteria is beyond the scope of this investigation. Among the criteria considered, the focus of this work is set on the environmental aspect.

An environmental assessment approach following the notion of sustainability must attempt to evaluate all potential impacts that a process can cause on the different environmental compartments, not only on a site-specific scale but along the complete network of supply chains to run the process, i.e. *life-cycle*. An approach based on the principles of life-cycle thinking is a necessary step in this direction.

Much efforts have been carried out in the last 15 years to develop life-cycle thinking approaches, e.g. the environmental life-cycle assessment (LCA), which have led to the standardisation of the LCA methodology and its positioning and acceptance as a tool that aims towards a holistic process assessment from a systemwide perspective. However, it has to be acknowledged that no single assessment tool can cover all relevant aspects related to environmental assessment making it necessary to apply a combination of methods.

In order to illustrate the need of combining several assessment tools and the limitations of part of current methods available in LCA, e.g. impact assessment methods for toxic emissions, two end-of-pipe processes dealing with the elimination of toxic compounds from waste waters and sediments have been studied. The elements composing the integrated approach for assessing and optimising treatment processes are:

- a) Economic analysis to determine treatment costs
- b) Environmental assessment based on a combination of a LCA-based approach complemented with eco-toxicological investigations to assess the quality of the treated materials and potential toxic impacts when they are discharged in the aquatic environment

Although it is clear that on the first instance end-of-pipe technologies do not represent an option that fully fits into the concept of sustainability, they are considered as a last resource to prevent pollution or higher risks to the environment. Two end-of-pipe processes are studied in this investigation for the following reasons:

- a) Treatment and remediation processes illustrate best the methodological challenges of attempting an approach based on life-cycle thinking for processes traditionally assessed from a *site-specific* perspective.
- b) The analysis of treatment processes evidences the need to combine existing tools for process assessment of technologies dealing with toxic emissions and to identify their synergies, e.g. the combination of an *effect-oriented* approach (based on bioassays) with an *inventory-oriented* approach such as life-cycle assessment.

The first process studied was a laboratory scale process to treat dockyard waters contaminated with copper, zinc and tributyltin (TBT). The elimination of the heavy metals was done by means of flocculation with ferric salts, while TBT was decomposed by means of electrolysis.

The main task consisted in developing the electrochemical treatment process to eliminate TBT because conventional water treatment processes are not suitable to reach a final TBT concentration of 100 ng/L Sn. Two anode materials for the electrolysis were tested: boron-doped diamond anodes (the support material was niobium and the doping level of boron was 2000 ppm) and titanium coated with iridium dioxide (Ti/IrO<sub>2</sub>). The former is a novel material with exceptional properties for hydroxyl radical generation, whilst the latter is a commercially available material.

The results of the assessment showed that it was possible to destroy organotins down to the target concentration with both anode materials exhibiting similar degradation rates. Nevertheless it was necessary to add a granular activated carbon (GAC) adsorption unit to eliminate AOX formed during the electrolysis and residual oxidants and reduce the high toxicity levels indicated by the bioassays. The life-cycle assessment of this process revealed that the most environmentally "costly" operation unit was electrochemical treatment (compared to flocculation and GAC) and therefore was subjected to optimisation.

A multiobjective optimisation (MO) approach was needed to optimise the operation of the electrochemical reactor in terms of treatment costs and life-cycle impacts (depletion of abiotic resources, global warming and acidification effects). The MO problem was solved using the  $\varepsilon$ -constraint method to obtain the non-inferior solutions for the criteria considered. Operating with Ti/IrO<sub>2</sub> resulted advantageous mostly due to the lower anode material costs. To select the "best" operation conditions out of the non-inferior curve, the point closer to a reference point representing the best theoretical performance that the electrolysis could achieve was selected (the best operating conditions obtained were: employing Ti/IrO<sub>2</sub> anodes at a current density of 9.5 mA/cm<sup>2</sup>, which resulted in treatment costs of 1.18  $\epsilon$ /m<sup>3</sup>, required 72.8 MJ of fossil energy per m<sup>3</sup> and emission of 6.0 kg CO<sub>2</sub> equivalents and 0.034 kg SO<sub>2</sub> equivalents per m<sup>3</sup>).

The second process was a pilot scaled process to remediate TBT contaminated sediments by means of electrolysis. The sediment throughput of the plant was 0.2 t/h. The process was able to decrease TBT down to the target 100  $\mu$ g/kg in the range of 4.4 to 6.6 mA/cm<sup>2</sup> with treatment costs between 20 to 23 €/t. Similarly to the waste water treatment process, the LCA methodology applied resulted unsuitable to assess the behaviour of toxicity of the sediment during treatment. TBT and PAH decreased but heavy metals and PCB were not affected by treatment. Although the concentrations of these pollutants of concern decreased or remained constant, the effect-oriented approach (ecotoxicological test investigation) indicated high toxicity of the sediment. By-products (e.g. AOX) and residual oxidants were the cause of these effects.

These examples showed the synergies between inventory- and effect-oriented approaches for assessment of processes dealing with toxic emissions. In addition, the compatibility of LCA with site-specific assessment tools to improve the quality of environmental assessments was demonstrated, as well as its compatibility with multi-criteria tools for optimisation and integration of environmental and economic criteria in a sustainability-oriented approach.