Application of the Enhanced Dynamic Causal Digraph Method to Wastewater Treatment Process

Hui Cheng, Michela Mulas, Sirkka-Liisa Jämsä-Jounela

Department of Biotechnology and Chemical Technology

Laboratory of Process Control and Automation

TKK, Finland
Motivations

Wastewater treatment (WWT) process is a complicated process where sensors and equipment are operated at harsh conditions.

Tremendous scope for improvement of fault detection and isolation methods.

Benefits

- reduce monitoring costs
- consistent water quality monitoring
- increased consistency by rapid detection and correction of faults
- reduction in human errors

Objective

Apply Enhanced Dynamic Causal Digraph Method to Wastewater Treatment Processes for Fault Diagnosis.
The Enhanced Dynamic Causal Digraph Method

Process knowledge and simulation software are the only pre-requisites to test the method.

The proposed method performs the fault detection and isolation as follows:

1. **Causal Digraph Modeling**
2. **Fault Scenarios Study**
   - Process Fault
   - Sensor Fault
3. **Fault Diagnosis**
   - Generate the global (GR) and local residuals (LR)
   - Detect a possible abnormality in the residual signals
   - Locate the primary fault and identify its nature by means of the fault isolation and nature rules
4. **Analysis of Results**
Outline

Process Study

Causal Digraph Model

Fault Scenarios

Fault Diagnosis

Conclusions
Process Description

Inside a biological WWT plant, the **Activated Sludge Process (ASP)** is the most common used technology to remove organic pollutant from wastewater.

**Benchmark Simulation Model No.1 (BSM1)** proposed by the IWA-COST group

**Nitrogen and Carbon Compounds Removal**

The BSM1 characterizes the plant including plant layout, specific model parameters and a detailed description of the influent flowrate and compositions.
Process Models

The benchmark is based on two internationally accepted process models

**Settler**
- Thickening and clarification processes take place here
- It is modelled as a stack of layer by means of the **Takacs Model**

**Bioreactor**
- It consists of two anoxic (Denitrification) followed by three aerobic (Nitrification) zones
- They are modelled with the **Activated Sludge Model No.1**
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\begin{align*}
\frac{dX}{dt} &= \mu(S) - bX \\
\frac{dS}{dt} &= -\frac{1}{Y} \mu(S) X \\
\mu(S) &= \hat{\mu} S \frac{S}{K_S + S}
\end{align*}
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Process Models

The ASM1 consists of 13 state variables and 8 process reactions

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**Composite variables**

\[
COD = S_I + S_S + X_I + X_S + X_{BH} + X_{BA} + X_P
\]

\[
TSS = 0.75(X_I + X_S + X_{BH} + X_{BA} + X_P)
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In the secondary settler model all the particulate components are lumped together
Process Simulation

Bioreactor and settler are coupled together in Matlab/Simulink.

Testing environment for the enhanced dynamic causal digraph method.
Outline

Process Study

Causal Digraph Model

Fault Scenarios

Fault Diagnosis

Conclusions
Causal Digraph Model

The Causal Digraph Model construction is done from the first principle model

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Measured Variables

- COD
- TSS

Estimated Variables

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The overall Causal Digraph Model represents the cause-effect relationships between $S_O$ and $S_{NO}$ in the tanks.

\[
\frac{dS_O}{dt} = \frac{Q}{V} (S_{O_{in}} - S_O) + K_{L,a}(S_{O_{in}}^* - S_O) - \mu_H \frac{1 - Y_H}{Y_H} \frac{S_S}{S_K + S_S + S_{O,H} + S_O} X_{BH}
\]
\[
- \mu_A \frac{4.57 - Y_A}{Y_A} \frac{S_{NH}}{K_{NH} + S_{NH} + S_{O,H} + S_O} X_{BA}
\]

\[
\frac{dS_{NO}}{dt} = \frac{Q}{V} (S_{NO_{in}} - S_{NO}) - \mu_H \frac{1 - Y_H}{2.86Y_H} \frac{S_S}{K_S + S_S + S_{O,H} + S_O} S_O \eta_E X_{BH}
\]
\[
- \mu_A \frac{1}{Y_A} \frac{S_{NH}}{K_{NH} + S_{NH} + S_{O,H} + S_O} X_{BA}
\]

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Causal Digraph Model

Fault Scenarios

Fault Diagnosis

Conclusions
Fault Scenarios

- 28 days are simulated with the influent flow and load compositions provided in the BSM1
- 2 faulty days are considered (14–16)

Two fault scenarios were selected to study based on the process knowledge:

**Scenario I**

The change in the biomass growth rate due of high concentration of toxic metal in the influent wastewater is considered.

**Scenario II**

The fault of the oxygen sensor is represented and analyzed.
Fault Scenarios

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**Process Fault**

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The fault of the oxygen sensor is represented and analyzed

**Sensor Fault**
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Diagnosis Results for Fault Scenario I

Global Residuals are calculated for $S_O$ and $S_{NO}$
Diagnosis Results for Fault Scenario I

Local Residuals are calculated for $S_O$ and $S_{NO}$.
Diagnosis Results for Fault Scenario I

\[
\frac{dS_2}{dt} = \frac{Q}{V} (S_2^{in} - S_2) + K_{L,a} (S_3^{in} - S_2)
\]

\[
- \frac{1 - Y_H}{Y_H} \left( S_5 \frac{S_5}{K_S + S_5} \frac{S_0}{K_{O,H} + S_0} - X_{BH} \right)
\]

\[
- \frac{4.57 - Y_A}{Y_A} \left( S_{NH} \frac{S_0}{K_{NH} + S_{NH} K_{O,A} + S_0} \right) - X_{BA}
\]

\[
\frac{dS_{NO}}{dt} = \frac{Q}{V} (S_{NO}^{in} - S_{NO})
\]

\[
- \frac{1 - Y_H}{Y_H} \left( S_5 \frac{K_{O,H}}{K_S + S_5} \frac{S_0}{K_{NO} + S_{NO}} \eta X_{BH} \right)
\]

\[
- \frac{1}{2.86 Y_H} \left( S_{NH} \frac{S_0}{K_{NH} + S_{NH} K_{O,A} + S_0} \right) - X_{BA}
\]

\[
- \frac{\mu A}{Y_A} \left( S_5 \frac{S_0}{K_{NH} + S_{NH} K_{O,A} + S_0} \right) - X_{BA}
\]
Diagnosis Results for Fault Scenario II

Global Residuals

Only variable $S_{O,5}$ is detected
Diagnosis Results for Fault Scenario II

Local Residuals

The individual local residual for variable $S_{O,w}$ with the input $S_{O,5}$ as measurement was detected. This implies that the fault on the variable $S_{O,5}$ is a measurement fault.
Diagnosis Results for Fault Scenario II

From the measurements for variables $S_{O,5}$, $S_{O,w}$ and $S_{O,1}$, it can be seen that during the days 14-16, the variables $S_{O,w}$, $S_{O,1}$ seem to have the fault, but actually the method is able to find the real fault in on the sensor of the $S_{O,5}$.
Diagnosis Results for Fault Scenario II
Outline

Process Study

Causal Digraph Model

Fault Scenarios

Fault Diagnosis

Conclusions
Conclusions

The enhanced casual digraph reasoning method for fault diagnosis was applied to the activated sludge process

Two fault scenarios were tested

**Process fault**
The method was able to handle it

**Sensor fault**
The correct node was detected

*Future Development*

- The preliminary study is limited by the assumption that the toxic affects only one tank. In future, fault in different tanks can be considered and FTC strategy can be designed
- The estimated size of the sensor fault can be used to design FTC for the aeration controller