

## Reconfiguration of an Industrial Steam Generator using Bond Graph Modelling

**Abstract:** In this paper, we survey some recent advances made in the field of bond graph modelling and show that bond graph modelling method is well suited to solve modelling, fault diagnosis and fault tolerant control problems in complex process engineering systems. We present a case study of development and implementation of fault tolerant control scheme for a steam generator process. Steam generator is a safety-critical complex thermo-fluid process, which involves storage and transport of under-saturated and saturated fluids, as well as phase transformations. Bond graph modelling, which is a unified tool for multi-energy domain system representation, is used to model the process. Moreover, the fault indicators are directly obtained from the bond graph model. Causal paths in the model are used to determine various redundancies, which are then used to determine possible system reconfigurations and operating modes, by taking various operating constraints (equipment availability, saturations, power ratings, etc.) into consideration. An academic example is used to explain the steps involved in the analysis of fault indicators, fault isolation, system recovery, operating modes, transition schemes, and selection of appropriate control laws. Implementation of the developed algorithms in a supervision system for the steam generator process and some experimental results from the process, during nominal and reconfigured operations, are presented.

**Keywords:** bond graph modelling, analytical redundancy, fault signature, fault detection and isolation, operating mode, fault tolerant control, fault accommodation, reconfiguration.

### 1. INTRODUCTION

Process supervision plays a key role in safe operation of industrial processes. The term ‘Supervision’ means a set of tools and methods used to operate a process in normal situation as well as in the presence of failures or undesired disturbances. Supervision systems mainly perform two tasks: Fault Detection and Isolation (FDI) and decision making to recover from the fault. The presence of a fault is detected at the monitoring level, which determines whether the process is in normal operation or not. The tools associated with diagnosis are executed after detection of abnormal process state. Fault Tolerant Control (FTC) is performed in situations where parameters or constraint structures change due to a fault.

FTC is performed through fault accommodation and/or system reconfiguration. In fault accommodation, the objective is to control the system under actual constraints. In system reconfiguration, part of the actual faulty system is replaced by another one, *e.g.* selection of alternative input and output for a controller. FTC approaches can be further classified into two categories: passive approach (*e.g.* robust control) and active approach (*e.g.* adaptive control). In active FTC, plant faults are diagnosed (FDI and parameter estimation) and subsequently the controller is redesigned for fault accommodation.

In a three-part review, Venkatasubramanian *et al.* (2003a, 2003b, 2003c) discussed different approaches for FDI. In this paper, FDI procedure is based on Analytical Redundancy Relations (ARR) (Åström *et al.*, 2001; Blanke *et al.*, 2003), for which a definite and accurate mathematical model is needed. Karnopp *et al.* (1990), Mukherjee *et al.* (2000), and Borutzky (2004) have shown that bond graph (BG) modelling is a unified multi-energy domain modelling method, which can be applied to model various engineering systems, including process engineering systems (Ould Bouamama, 2003a; Thoma and Ould Bouamama, 2000).

Furthermore, Sueur and Dauphin-Tanguy (1991), and Dauphin-Tanguy *et.al.* (1999) have developed principles for studying the structural control properties (controllability, observability, etc.) of systems by analysing the causalities on BG models. Tagina *et al.* (1995) developed a methodology to optimise sensor placements and determine hardware redundancies using the structural control properties obtained from BG models. Various developments by using BG modelling in the field of control engineering (Gawthrop, 1995) have been reported in literature, e.g. system inversion (Gawthrop, 2000a; Ngwompo *et.al.*, 1996; Ngwompo *et.al.*, 1999a), I/O decoupling, system identification (Gawthrop *et.al.*, 1992), parameter estimation (Gawthrop, 2000b; Gawthrop *et.al.*, 2000c), and actuator sizing (Ngwompo and Scavarda, 1999b). It will be shown in this paper that these recent developments in the field of control engineering using BG based physical models can be readily used to develop fault accommodation algorithms.

## 2. BOND GRAPHS FOR QUANTITATIVE MODEL BASED FDI

An ARR is a constraint between a set of known process variables. ARRs link the time evolution of the variables when the system operates according to its normal operation model. ARRs are evaluated by using parameter values and measurements from the monitored system to generate residuals, which are then used for FDI.

In bond graph terms, a residual  $r = f(\text{De}, \text{Df}, \text{Se}, \text{Sf}, \text{MSe}, \text{MSf}, u, \theta) = 0$ , where  $u$  is the controller output vector,  $\theta$  is the vector of parameters, and  $f$  is a constraining function. Constraints are formed by the junction structure and constitutive relations of the elements. For thermo-fluid systems, these constraints may take various forms, e.g. continuity equation, Bernoulli's equation, conservation of mass and energy. ARR can be obtained from BG model through an algorithmic procedure developed in Ould Bouamama *et al.* (2003b).

For structurally independent residuals  $r_i = f_i(K_i)$ , where  $i=1\dots n$ , and  $K_i$  is the set of known variables; the following property is satisfied :  $K_i \neq K_j \forall i \neq j$ , where  $i, j = 1\dots n$ . A decision procedure generates the alarm states needed to detect faults. Robust decision procedures minimise misdetection and false alarms by treating the residual noises. In passive FDI, a decision procedure  $\Theta(r_1, r_2, \dots, r_n)$  tests each residual,  $r_i$ , against a fixed or adaptive threshold,  $\delta_i$ , to generate a coherence vector,  $C$ . The elements of  $C$ ,  $c_i$  ( $i=1\dots n$ ), are determined from

$$c_i = \begin{cases} 0, & \text{if } r_i \text{ is bounded by } \delta_i; \\ 1, & \text{otherwise.} \end{cases}$$

A fault is detected, when  $C \neq [0, 0, \dots, 0]$ , i.e. at least at least one residual exceeded its threshold. A Fault Signature Matrix (FSM), which describes the participation of various components (physical devices, sensors, actuators and controllers) in each residual, is used to isolate faulty components. The elements of FSM, say  $S$ , are determined as:

$$S_{ji} = \begin{cases} 1, & \text{if } i^{\text{th}} \text{ ARR contains variables of } j^{\text{th}} \text{ component;} \\ 0, & \text{otherwise.} \end{cases}$$

Note that FSM can be determined from causal paths on a BG model. Structured residuals (Blanke *et.al.*, 2003) are designed in such a way that each residual is sensitive to a subset of faults and insensitive to other faults. A set of residuals in which every residual responds to one and only one fault is called structured and directional (also called diagonal)

allows isolation of multiple faults. Different forms of ARRs are equivalent to assignment of different causalities on a BG model.

### 3. BOND GRAPHS FOR FTC

The objective of FTC is to prevent local faults developing into serious failures. FTC requires redundant hardware in the system, which can be used in the case of fault(s) in one or more components, *e.g.*, sensors and actuators. The minimum set of actuators and sensors required for operating a system is defined by the controllability and observability conditions, which are elegantly determined from a BG model (Sueur and Dauphin-Tanguy, 1991).

FTC requires that faults can be isolated. Reconfiguration can be performed, if redundant hardware for the faulty component is available. However, redundant hardware cannot be indiscriminately placed. The objective of actuator and sensor placement scheme for FTC is to maintain controllability and observability of the process at all times, *i.e.* even after loss of key hardware. The term key hardware means the minimum set of actuators and sensors needed to operate and monitor the process.

The necessary conditions for functional recoverability (Åström *et.al.*, 2001) from faults is that with the remaining actuators and sensors, the system is functionally controllable and observable, the system can be identified and its parameters can be estimated. This is formally termed as the model matching technique. System identification and parameter estimation from a BG model is achieved by using techniques developed in Gawthrop *et.al.* (1992), Gawthrop (2000b), and Gawthrop *et.al.* (2000c). If some key sensors are lost, then their measurements can be reconstructed using an observer and used to control the system without changing the control law.

One of the active methods for FTC is predictive control, which handles multi-variable problems, takes care of actuator limitations, and allows operation closer to constraints (Åström *et.al.*, 2001). Constraints for predictive control are usually specified in terms of actuator ranges, actuator slew rates and output levels. Actuator ranges and slew rates are not only determined from the actuator limitations, but also from the type of power supply and power modulating device. These constraints are verified through system inversion, which provides the trajectory of effort and flow variables (consequently the power) needed to produce specified outputs. In the design phase, actuators are selected (actuator sizing problem) from model inversion (corresponding to desired output specifications). Both system inversion and actuator sizing require analytical models. BG model based system inversion techniques are developed in Gawthrop (2000a), Ngwompo *et.al.* (1996) and Ngwompo *et.al.* (1999a). The actuator sizing problem is studied in Ngwompo and Scavarda (1999b) by using BG models.

In FTC, when controllers are reconfigured (*e.g.* by changing the set point) to transit the system from one trajectory to another, instantaneous input requirements may not be achieved with the available sources. Then the objective is to determine an appropriate output specification, which can be accommodated by the input sources. This problem is identical to that of actuator sizing. Another method to accommodate the fault is to transit from one operating condition to another by using a step-by-step procedure, *e.g.*, increasing a controller set point from one value to another in multiple steps such that actuator constraints are not violated in any step. This way of FTC is often called a receding horizon control. Determination of the number of steps and the step size is again an actuator sizing problem.

From the preceding survey of available techniques, we find that BG modelling method is sufficiently developed to solve FDI and FTC problems in complex process engineering systems.

#### 4. BOND GRAPH MODELLING OF A THERMO-FLUID PROCESS

A simple two tank system (Figure 1), in which Tank<sub>1</sub> and Tank<sub>2</sub> are connected by a valve V<sub>1</sub>, and fluid from Tank<sub>2</sub> is discharged to the environment through a valve, V<sub>2</sub>, is considered. Tank<sub>1</sub> is equipped with a pump and a heater. The purpose of the system is to provide a continuous flow to the consumer.

##### [Figure 1]

The power variables to model hydraulic domain are mass flow rate ( $\dot{m}$ ) and fluid pressure ( $P$ ); whereas those for thermal domain are enthalpy flow rate ( $\dot{H}$ ) and temperature ( $T$ ) (Ould Bouamama, 2003a; and Thoma and Ould Bouamama, 2000). The pseudo BG of the process is shown in Figure 2, where CETF represents the Coupling Element for Thermo- Fluids (Ould Bouamama, 2006). Two possible causal forms of CETF and the corresponding equations are given in Table 1, where  $c_p$  is the specific heat capacity of the fluid. Note that the temperature of downstream side ( $T_2$ ) does not appear in the constitutive relations of CETF.

##### [Table 1]

The top part of the BG model concerns hydraulic domain and the bottom part concerns thermal domain, where  $C_H = A/g$ ,  $C_T = mc_p$  and  $A$  is the cross-sectional area. The states associated with the storage elements (C-elements) in the hydraulic and thermal domains are total mass ( $m$ ) and total enthalpy ( $H$ ), respectively.

##### [Figure 2]

#### 4.1 Minimal Sensor Placement for thermo-fluid processes

The minimum requirement for implementation of FDI and FTC scheme is that the process should be both controllable and observable. If a process is observable, then all faults in the process can be detected, but fault isolation is achieved by installing more sensors. More sensors and actuators are needed for fault accommodation through reconfiguration. By applying structural controllability test conditions (Sueur and Dauphin-Tanguy, 1991), we find that for the example process, the hydraulic part of the process is structurally controllable; whereas the thermal part is uncontrollable. Note that in thermo-fluid models for under-saturated fluid, there is no causal path from thermal domain to hydraulic domain. However, in saturated fluids, thermal and hydraulic domains are coupled, *i.e.* thermodynamics influences hydrodynamics and vice versa.

The sensor placement to ensure structural observability is discussed next. Sensor placement for structural controllability follows a similar approach.

#### 4.2 Sensor Placement for Observability of thermo-fluid processes

In the process shown in Figure 1, the fluid temperature inside the Tank<sub>1</sub> is measured by a sensor  $T_1$ , while a level sensor  $L_2$  measures the level in the Tank<sub>2</sub>. In Figure 2, element  $C_{T2}$  does not have causal path to any detector because effort information cannot pass through bond 21 attached to CETF. Hence the attainability or necessary condition (Sueur and Dauphin-Tanguy, 1991) fails and the process is not observable for the given sensor configuration.

##### [Figure 3]

Let us consider another configuration (Figure 3), where the temperature sensor is installed in Tank<sub>2</sub> instead of Tank<sub>1</sub>. Each integrally causalled storage element in the corresponding BG model (Figure 4) has a causal path linking it to a detector; thus satisfying the attainability condition. The second condition, *i.e.*, the sufficient condition (Sueur and Dauphin-Tanguy, 1991) for structural observability is tested using preferred derivative causality, as shown in Figure 5. It is seen that both necessary and sufficient conditions for structural

observability is satisfied and hence the two sensors in the process constitute minimum sensor architecture.

[Figure 4]

[Figure 5]

### 4.3 Sensor placement for FDI and FTC

For fault isolation and accommodation, more sensors are to be installed in the process to obtain structured residuals. When a fault is too severe, one may go for reconfiguration by using stand-by devices, called hardware redundancy, to accommodate the fault. Two types of redundancy are possible for actuators and sensors: deduced and direct redundancy. These issues are explained with the help of an academic example, in the next section.

## 5. ACADEMIC EXAMPLE

[Figure 6]

Let us consider an academic example process as shown in Figure 6, in which a PI controller acts on a pump, two On-Off controllers act on a heater inside Tank<sub>1</sub> and there are some redundant sensors. On-Off<sub>2</sub> is a stand-by controller meant for FTC, when  $T_1$  becomes faulty. One pump out of the two remains operative and the other is a standby or material redundancy. We assume that valves  $V_1$  and  $V_2$  are never fully closed.

It is assumed that controller outputs known:  $U_p$  and  $U_o$ , for PI and On-Off controllers, respectively. Outflows from the pump and heater are also measured ( $Q_p$  and  $Q_T$ , respectively). The characteristic functions for actuators (pump and heater) and controllers (PI and On-Off) are defined as  $\Phi_p, \Phi_h, \Phi_{PI}, \Phi_{OnOff}$ , respectively.

### 5.1 Determination of Direct and Deduced Redundancies

The BG model of the system in preferred derivative causality (Figure 7) is analyzed to determine the redundancies. First of all, essential sensors or base sensors from the view point of FDI are identified (in this case, we assume them to be  $L_1, L_2, T_1$  and  $T_2$ ). Sensor redundancies are evaluated with respect to the base sensors, *i.e.* causalities of base sensors are inverted. Bond causalities of some sensors must be inverted to assign preferred derivative causality to storage elements (to maintain process observability, *i.e.* minimum sensor set); therefore those sensors are added to the list of base sensors.

[Figure 7]

There are two occasions when detector causality is not inverted, which lead to two types of redundancy. Where direct causal paths exist from one or more sensors in inverted causality to the redundant sensor, without involving any passive element (I, C or R) or two-port element (TF or GY), the resulting redundancy is termed *direct* or hardware redundancy. Sensor  $L_3$  falls in this category. Where causal paths to the sensor in non-inverted causality involve any passive or two-port element, the resulting redundancy is called *deduced* or functional redundancy. Sensor  $F_1$  falls under this category.

### 5.2 Analytical Redundancy Relations (ARRs)

ARRs for the process are obtained from the BG model, in Figure 7, by following the methodology developed in Ould Bouamama *et. al.* (2003b). Because the process has ten outputs, ten ARR<sub>s</sub> are obtained:

$$ARR_1 = U_p - \Phi_{PI}(L_1) = 0,$$

$$ARR_2 = Q_p - \Phi_p(U_p) = 0,$$

$$\begin{aligned}
ARR_3 &= U_o - \Phi_{\text{OnOff}}(T_1) = 0, \\
ARR_4 &= Q_T - \Phi_h(U_o) = 0, \\
ARR_5 &= Q_p - \frac{A_1}{g} \cdot \frac{d}{dt}(\rho \cdot g \cdot L_1) - C_{d1} \cdot \sqrt{\rho \cdot g \cdot (L_1 - L_2)} = 0, \\
ARR_6 &= C_{d1} \cdot \sqrt{\rho \cdot g \cdot (L_1 - L_2)} - \frac{A_2}{g} \cdot \frac{d}{dt}(\rho \cdot g \cdot L_2) - C_{d2} \cdot \sqrt{\rho \cdot g \cdot L_2} = 0, \\
ARR_7 &= L_3 - L_2 = 0, \\
ARR_8 &= F_1 - C_{d1} \cdot \sqrt{\rho \cdot g \cdot (L_1 - L_2)} = 0, \\
ARR_9 &= Q_T + Q_p \cdot c_p \cdot T_{in} - \rho A_1 c_p \cdot \frac{d}{dt}(L_1 T_1) - C_{d1} \cdot \sqrt{\rho \cdot g \cdot (L_1 - L_2)} \cdot c_p \cdot T_1 - \frac{T_1 - T_0}{R_1} = 0, \\
ARR_{10} &= C_{d1} \cdot \sqrt{\rho \cdot g \cdot (L_1 - L_2)} \cdot c_p \cdot T_1 - \rho A_2 c_p \cdot \frac{d}{dt}(L_2 T_2) - C_{d2} \cdot \sqrt{\rho \cdot g \cdot L_2} \cdot c_p \cdot T_2 - \frac{T_2 - T_0}{R_2} = 0.
\end{aligned}$$

### 5.3 Fault Signature Matrix (FSM)

The FSM is obtained from the ARR, when they are available in symbolic form. Alternatively, FSM can be constructed from causal paths. The components involved in a residual associated to a sensor are those, which have a causal path to that sensor in differentially causalled BG model plus the sensor itself. For example, the followings are the causal paths to  $L_1$  in Figure 7:

$$L_2 \rightarrow e_{10} \rightarrow e_9 \rightarrow e_8 \rightarrow e_6 \rightarrow e_5 \rightarrow R_{V1} \rightarrow f_5 \rightarrow f_4 \rightarrow f_{25} \rightarrow f_{28} \rightarrow f_{29} \rightarrow L_1$$

$$Q_p \rightarrow f_1 \rightarrow f_2 \rightarrow f_{25} \rightarrow f_{28} \rightarrow f_{29} \rightarrow L_1$$

$$C_{H1} \rightarrow f_3 \rightarrow f_{25} \rightarrow f_{28} \rightarrow f_{29} \rightarrow L_1$$

From these causal paths, the components involved in the residual  $r_5$  are obtained as  $K_5 = [L_1, L_2, Q_p, C_{H1}, R_{V1}]$ , which can be written in the terms of components as  $K_5 = [L_1, L_2, Q_p, \text{Tank}_1, V_1]$ . The FSM of the process is given in Table 2, where the last column ( $I_b$ ) indicates fault isolability by using a binary index. Note that  $\text{Tank}_2$  and  $V_2$  are the only components, for which faults cannot be isolated (because they have identical fault signatures  $[0,0,0,0,0,1,0,0,0,1]$ ). More sensors are needed to isolate faults in these two components, e.g. by placing a flow sensor at the output.

[Table 2]

### 5.4 Sensor and Actuator Loss

A process may continue to operate as long as all critical faults can be detected (may not be isolated) and it remains observable and controllable. However, for continuous monitoring of the process, ARRs and FSM must be modified every time a fault occurs. We consider three categories of sensor failure.

**Case I:** Consider failure in a redundant sensor, e.g.  $F_1$  or  $L_3$ . Redundant sensors appear in only one ARR (a property of redundancy). Therefore, the corresponding ARR is removed from the set of ARRs and the FSM is modified by removing the row and the column corresponding to the sensor and the residual, respectively. There is no need to re-derive ARRs or FSM from the model, but fault isolability is recalculated.

**Case II:** Consider fault in a base sensor, say  $L_2$ , which has a direct hardware redundancy, with sensor  $L_3$ . Component  $L_3$  appears only in one residual,  $r_7$ . Then the following procedure applied: (1)  $ARR_7$  is removed from ARR's list and the column corresponding to residual  $r_7$  is removed from FSM, leaving nine ARR's and residuals. (2) In each ARR, variable  $L_2$  is replaced by  $L_3$  and signature (row) of  $L_2$  is copied to  $L_3$ . (3) Signature of  $L_2$  is removed from FSM and fault isolability is recalculated.

**Case III:** Consider the case, where a failed base sensor is replaced by another sensor, which is a deduced (functional) redundancy. This is not an easy task, because it involves symbolic algebra and the structure of the resulting ARR's can change significantly. However, by modifying the BG model and analyzing causal paths, one can easily obtain ARR's and FSM for the process.

When a process component or a base sensor without a redundancy fails, model must be reconstructed and ARR's and FSM have to be reconstructed.

Similar reconfiguration technique is needed for actuator failures.

### 5.5 Operating Modes (OMs) and Operating Mode Management

In order to avoid simultaneous attempt at performing incompatible reconfigurations, services offered by the components are organized into coherent subsets, called Operating Modes (*OM*). Each *OM* can be associated to a BG model (Ould Bouamama *et.al.*, 2005a). An automaton specifies the conditions to change from one *OM* to another.

A set of transition conditions  $b = \{b_{ij}\}$ , where  $b_{ij}$  (a boolean variable) indicates the required condition to move from  $OM_i$  to  $OM_j$ , is defined by analyzing the services offered by various devices, equipment availability and how the desired operating goals can be achieved. Maintenance of set of the available services is called *operating mode management*.

### 5.6 Parameter Estimation

Process faults cannot be accommodated as long as the fault is not quantified, i.e. fault parameters are not estimated. A bond graph based approach, called sensitivity bond graphs, was developed in Gawthrop (2000b) and Gawthrop *et.al.* (2000c) to estimate parameters of the system by using recursive least squares algorithm. Partial derivatives of the cost function with respect to parameters were used to derive a set of equations, which were then represented in a sensitivity bond graph form.

The standard recursive least squares optimization technique attempts to estimate the parameter values, which give minimum output error. One limitation of this algorithm is that the new parameter vector is assumed to be constant over the optimization time window. Clearly, assumption of parameters being constant over a given time window can be applied to identify abrupt faults, but this approach is not appropriate to handle intermittent or progressive faults.

However, usually there are many sensors in a FDI application, which allow using ARR's for fault quantification. Consider that a fault occurs due to which the residual is nonzero and that the fault can be identified as change in the value of parameter  $\theta_i$  (through fault isolation). The corresponding ARR can be written as  $ARR = f(u, \dot{u}, \dots; (\theta_1, \theta_2, \dots, \theta_i, \dots, \theta_n); y, \dot{y}, \dots)$ , where  $u$  is input vector,  $\theta = \{\theta_1, \theta_2, \dots, \theta_n\}$  is the parameter vector and  $y$  is the output vector. Then the new parameter value  $\hat{\theta}_i$  can be estimated, either algebraically or numerically, from the relation  $f(u, \dot{u}, \dots; (\theta_1, \theta_2, \dots, \hat{\theta}_i, \dots, \theta_n); y, \dot{y}, \dots) = 0$ .

### 5.7 Actuator Capacity Testing

Once the fault magnitude is estimated, then the next step is to accommodate the fault by suitably changing the control laws. Then process of finding an input sequence to satisfy a constraint given in the form of an output sequence is called system inversion. Let us consider the word bond graph of a system given in Figure 8, in which different power variables are marked. Each of these power variables usually have a constraint, e.g. how much maximum current can be drawn from an electrical source? Let us consider that the constraints are as follows:  $|e_m(t)| \leq E_m$ ,  $|f_m(t)| \leq F_m$ ,  $|e_m(t) \cdot f_m(t)| \leq W_m$ ,  $|e_a(t)| \leq E_a$ ,  $|f_a(t)| \leq F_a$ ,  $|e_a(t) \cdot f_a(t)| \leq W_a$ ,  $\forall t \in [0, T]$ , where  $T$  is the time required to reach the steady state. This is exactly an actuator sizing problem (Ngwompo and Scavarda, 1999b).

[Figure 8]

System inversion is performed using bicausality notations, where source sensor (SS) elements (Gawthrop, 2000a and Gawthrop, 2000b) are used to specify the desired outputs. Inversion of a BG model for actuator sizing using a SS element in place of a prescribed output flow is shown in Figure 9.

[Figure 9]

A representative plot of the time evolution of different variables, in the constraint space (Ngwompo and Scavarda, 1999b) is shown in Figure 10. The hyperbolic curves represent constraints on power and the non-shaded area in the middle of each plot is the admissible operating regime.

[Figure 10]

The objective is to find an output profile (e.g. maximum slew rate), characterised by some parameter, say  $\alpha$ , and the corresponding input laws, for which the operating constraints are satisfied.

## 6. OPERATING MODES OF THE ACADEMIC EXAMPLE

For the academic example, start, stop and normal operating mode are defined as  $OM_1$ ,  $OM_2$  and  $OM_3$ , respectively. A few other operating modes are discussed in the following.

**Case I:** Temperature sensor  $T_1$  is faulty and the heater is controlled by another controller, On-Off<sub>2</sub>, using sensor  $T_2$ . We have shown before that the process remains observable after  $T_1$  is lost. This operating mode is called  $OM_4$ .

**Case II:** Level sensor  $L_1$  is faulty in  $OM_5$ . However,  $L_1$  can be estimated from ARR<sub>8</sub> in terms of  $L_2$  and  $F_1$ , as follows:

$$ARR_8 = F_1 - C_{d1} \cdot \sqrt{\rho \cdot g \cdot (L_1 - L_2)} = 0 \Rightarrow L_1 = L_2 + \frac{F_1^2}{\rho \cdot g \cdot C_{d1}^2}.$$

Alternatively,  $L_1$  can be obtained in terms of  $L_2$  only by solving ARR<sub>5</sub>. This approach is not preferred because we need a derivative of  $L_2$ . Note that if  $L_1$  is faulty and  $L_2$  is unavailable, then system directly enters  $OM_6$ .

**Case III:** Level sensors  $L_1$  and  $L_2$  both are faulty in  $OM_6$ . A reconfiguration using sensor  $L_3$  is performed in the similar way as  $OM_5$ . Then the following OM sequences result:  $OM_1 \rightarrow OM_3 \rightarrow OM_5 \rightarrow OM_6 \rightarrow \dots \rightarrow OM_2$  or  $OM_1 \rightarrow OM_3 \rightarrow OM_6 \rightarrow \dots \rightarrow OM_2$ .

**Case IV:** One pump has failed in  $OM_8$ . Since the process consists of a redundant pump (material redundancy), the other pump is used.



**Case V:** Valve  $V_1$  is blocked in  $OM_{13}$ . If the objective is to maintain a constant flow rate to the consumer, then the level in Tank<sub>2</sub> must be constant, which consequently requires higher water level in the Tank<sub>1</sub>. The question now remains, by how much and at what rate we should increase the level set point in Tank<sub>1</sub>?

The new value for the level set point for Tank<sub>1</sub>, such that the steady state output of the system will match the output in the non-faulty case, is found to be

$$L_{1s}^* = \frac{C_{d1}^2}{C_{d1}^2 + C_{d2}^2} L_{1s} + \left( \frac{C_{d1}}{C_{d1f}} \right)^2 \left( 1 - \frac{C_{d1}^2}{C_{d1}^2 + C_{d2}^2} \right) L_{1s},$$

where,  $L_{1s}$  is the nominal level set point for Tank<sub>1</sub>,  $L_{1s}^*$  is the new estimated level set point for Tank<sub>1</sub>,  $C_{d1}$  and  $C_{d1f}$  are the discharge coefficients of the valve  $V_1$  in good and defective conditions, respectively, and  $C_{d2}$  is the discharge coefficient of the valve  $V_2$  in good condition. Using ARR for parameter estimation,  $C_{d1f} = (Q_p - C_{H1} \cdot (\rho \cdot g \cdot \dot{L}_1)) / \sqrt{\rho \cdot g \cdot (L_1 - L_2)}$ .

The fault can be accommodated, if  $V_1$  is not completely blocked ( $C_{d1f} \neq 0$ ), Tank<sub>1</sub> is able to accommodate the prescribed level without overflowing (geometrical constraint), and the pump is able to give enough flow, against the given pressure head. If we abruptly increase the level set point from  $L_{1s}$  to  $L_{1s}^*$ , the pump has to deliver huge amount of flow, instantaneously. Consider the trajectory  $L_1(t) = L_{1s} + \Delta L_s (1 - e^{-\alpha t})$ , where  $\Delta L_s = L_{1s}^* - L_{1s}$ , and  $\alpha > 0$  is a parameter to tune according to actuator limitations. The actuator sizing for the process is done using inverse model shown in Figure 11.

**[Figure 11]**

From the inverse model, the input flow is determined as:

$Q_p^* = A_1 \rho \alpha \cdot \Delta L_s e^{-\alpha t} + C_{d1f} \sqrt{\rho g (L_{1s} + \Delta L_s (1 - e^{-\alpha t}) - L_2)}$ . The pressure head, against which this flow works, is  $e_a = \rho g L_1(t)$  and the required power is  $e_a Q_p^*$ . The power modulator constraints can be determined similarly. The objective is to find a value of  $\alpha$  within the operating constraints of all actuator components.

This fault tolerant control involves three steps: (1) the PI controller is suspended, (2) pump is then operated according to the FTC law derived before to bring the level in Tank<sub>1</sub> sufficiently close to  $L_{1s}$  and (3) finally, the PI controller activated with new set point, which takes care of small deviations.

**Case VI:** This case corresponds to multiple non-overlapping faults, *e.g.* failure of  $T_1$  and  $L_1$ , discussed in Case I and II, respectively. Here, both the sensors are independently reconfigured.

Note that in the case of heater failure, leakages from tanks, failure of two pumps, etc., for which no reconfiguration or FTC option is available, the process is shut down. Also note that when  $L_1$ ,  $L_2$  and  $L_3$  are faulty, the observability condition fails (the difference between level in the two tanks can be obtained from the flow sensor  $F_1$ , but those levels cannot be individually estimated) and the process is shut down.

The management of operating modes and transition conditions is shown in Figure 12.

**[Figure 12]**

## 7. APPLICATION TO THE STEAM GENERATOR PROCESS

The steam generator process (Figure 13), which is a reduced scale model of part of a power plant and pilot installation, is situated at University of Lille-1. The Process and Instrumentation Diagram (P&ID) of the process is given in Figure 14.

### [Figure 13]

The plant is composed of a boiler with a capacity of 170 litres, a 55 KW heater, a steam expansion system, a condenser coupled with a heat exchanger, a storage tank and a feed water circuit. The boiler load is realised by the steam expansion system formed by a set of two valves ( $V_1$  and  $V_2$ ) and the condenser coupled with a heat exchanger. The boiler water level is controlled within  $\pm 3$  litres of a set point by switching on a pump. An On-Off controller acts on the heater to maintain boiler pressure within  $\pm 0.2$  bar of a pressure set point. Boiler, steam expansion system and the condenser are the most critical components of the installation. Therefore, many redundant sensors are used there.

The condensate level ( $L_{18}$ ) is controlled within  $\pm 0.5$  litres of a given set point by means of three on-off valves ( $V_3$ ,  $V_4$  and  $V_5$ ) placed between the condenser and the tank. The water supply system is made of two pumps ( $P_1$  and  $P_2$ ) and a pipe. At any given point of time, only one pump can be in operation and the other is redundant. The pump supplies water to the boiler and it is actuated by an on-off controller using the boiler water level (sensor  $L_8$ ).

### [Figure 14]

### [Figure 15]

This installation has been specifically designed to serve as a pilot plant to test FDI and FTC applications. It is possible to simulate most of the faults manually or automatically. Leakages from the condenser and the tank or the boiler are simulated by opening valves  $V_8$ ;  $V_9$  or  $V_{10}$ , respectively. Boiler output blockage is achieved by closing valve  $V_0$ . Faults on the sensors and actuator faults (heater or the pumps) are introduced by manipulating their power supplies from switch boards.

The BG model of the steam generator process has been developed in Ould Bouamama *et.al.*, (2006). In this paper, we adapt that model and assign it preferred derivative causality, as shown in Figure 15. From the BG model in preferred derivative causality, ARR and FSM have been derived and used for FDI in Medjaher *et. al.* (2006). Our objective is FTC, for which we determine different redundancies from the BG model. The list of redundancies is given in Table 3. Note that in the saturated regime, steam pressure and temperature are correlated, as given by the steam table or Mollier chart (function  $P_s2T_s$  in Figure 15).

### [Table 3]

Reconfiguration is possible, only when for failure of one or more base device(s), there are corresponding redundant devices available in good health. When two or more devices are redundant with a common base device, they are mutually redundant. The coupling between the supervisory layer and the base devices of the steam generator installation is determined from Table 3 and it is represented by a tree-structure in Figure 16.

### [Figure 16]

In Figure 16, basic functionalities required for process operation are listed and the associated devices needed to perform those functions are linked in a tree-structure. Where more than one device is available to perform the same task, branches are sequentially numbered indicating a hierarchical preference. Sometimes, equal preference (simultaneous use of devices) is given to all branches. Theoretically, a process can operate normally, as long as at least one device is available for each basic function. When a device fails, the branch associated with it is

removed and the system is reconfigured using the next device, according to the defined hierarchy, *e.g.* when  $P_7$  fails, it is reconfigured using  $T_6$  (if available). Note that boiler temperature is not directly linked to the supervisory layer.

### 7.1 Operating modes of the steam generator installation

- Preparation and Start mode ( $OM_1$ ): close  $V_0$ , allow control of boiler level and heater such that steam become saturated. Then open  $V_0$ .
- Shut down mode ( $OM_2$ ): when a fault detected, but cannot be isolated or when an isolated fault cannot be accommodated. Stop heater and pump, allow natural control of steam expansion system and the condenser until boiler pressure falls below a threshold and then shutdown the supervision and control systems.
- Normal operation mode ( $OM_3$ ): after start mode, when all controls are active and there are no faults in any device.
- Degraded operation modes
  - Condensate discharge valve failure ( $OM_4$ ): as long as one of the condensate discharge valves is non-faulty, continue operating the plant.
  - Steam expansion system fault ( $OM_5$ ): alter controller set point. If fault cannot be accommodated within given tolerance limits, enter manual operation mode.
  - Partial fault in pump ( $OM_6$ ): one pump is unavailable and the reconfigured control acts on the second pump, which is not operating with full efficiency.
  - Partial heater fault ( $OM_7$ ): heater is not delivering full power, but is enough to sustain the boiler pressure at given load.
- Reconfigured modes
  - Boiler level control ( $OM_8$ ): Upon failure of  $L_8$ , use  $L_9$ , if available.
  - Boiler pressure control ( $OM_9$ )
    - $OM_{9a}$ : Upon  $P_7$  failure, use  $T_6$  or  $T_5$ .
    - $OM_{9b}$ : Upon  $P_7$  and the sensor used in  $OM_{7a}$  failure, use the other temperature sensor.
  - Condenser level control ( $OM_{10}$ ): Upon failure of  $L_{18}$ , use  $L_{19}$ , if available.
  - Condenser pressure control ( $OM_{11}$ )
    - $OM_{11a}$ : If  $P_{15}$  has failed, use  $P_{16}$  for controlling downstream pressure.
    - $OM_{11b}$ : If  $P_{15}$  and  $P_{16}$  have both failed, use  $P_{13}$ .
    - $OM_{11c}$ : If  $P_{15}$ ,  $P_{16}$  and  $P_{13}$  have failed, use  $P_{27}$  and  $L_{18}$  or  $L_{19}$ .
    - $OM_{11d}$ : If all pressure sensors in condenser side have failed, use  $T_{17}$ .
  - Pump failure ( $OM_{12}$ ): Upon failure of  $P_1$ , use  $P_2$ , if available.
- Fault Accommodation mode ( $OM_{13}$ ): During steam expansion system fault, estimate the fault, *i.e.* whether a blockage or leakage. If it is leakage, then close  $V_0$  and transit to  $OM_2$  (shutdown mode). Otherwise, increase the boiler pressure set point and/or decrease the condensate level set point (more exposed tubes increase the rate of condensation, which result in pressure drop). The effective coefficient of discharge through  $V_1$  and  $V_2$  is estimated and then the desired pressure drop is calculated, which is then used to specify the boiler pressure and condenser level set points. Moreover, boiler pressure set point is constrained by the capacity of the pump to deliver flow against the new pressure head. The actuator capacity is verified through model inversion.
- Critical operation mode ( $OM_{14}$ ): With the available sensors, faults in all critical components can be detected, but faults in one or more components of the process cannot be isolated.

- Mutually exclusive operating modes ( $OM_{15}$ ): when FTC or reconfiguration of two or more mutually exclusive control loops is performed simultaneously, e.g.  $OM_{9a} + OM_{11a}$  (simultaneously  $P_7$  and  $P_{15}$  are faulty and they are reconfigured by  $T_6$  and  $P_{16}$ , respectively).
- Manual operation mode ( $OM_{16}$ ): For blockage in steam expansion system, operate  $V_1$  to achieve desired steam flow and pressure drop. If fault cannot be accommodated within given tolerance limits, transit to  $OM_2$ .
- Maintenance Mode ( $OM_{17}$ ): Operate full or part of the system to locate faults for repair action. FTC option is usually turned off, but continuous monitoring is desired for safety of maintenance workers.

## 7.2 Implementation of the integrated supervision platform

Commercial supervision software Panorama is used in this application. Gensym's G2 software is used to maintain the process database (DB) and the knowledge base (KB). The data acquisition scheme is shown in Figure 17. Process measurements are acquired by a program called FCTINTPP, where complicated mathematical calculations, such as the evaluation of the residuals, are performed.

### [Figure 17]

Several toolboxes (TBs) are used to develop an integrated supervision platform: TB 5.1 or ModelBuilder software (Ould Bouamama *et.al.*, 2005b) for modelling, TB 3.2 and TB 5.2 for robust FDI using temporal band sequences, TB3.7 for multivariate statistical process control based on principal component analysis (PCA), and TB 7.2 for alarm filtering, reconfiguration and FTC.

TB 5.1 generates the process model, symbolic ARRs, FSM and exports them in XML (eXtended Markup Language) form via the CCOM server (XML Blaster running with Java runtime and communicating over network through remote procedure calls by using TCP/IP). Data exchange between toolboxes is carried out by the CCOM server. Standard forms of network communication by using subscribe, publish, post, and point to point messaging protocols are implemented. Archived data for a specified duration can be obtained from Data Manager, which is implemented using G2.

Toolboxes are implemented using different programming languages and data structures. Therefore, the data exchange with other toolboxes in XML format requires bridges between the toolbox and the CCOM TCP/IP client component, e.g. C++ CCOM, G2 CCOM and Java CCOM bridges. The interaction between parts of the integrated supervision system is given in Figure 18.

### [Figure 18]

## 8. EXPERIMENTAL RESULTS

The interface for process monitoring, developed in Panorama, is shown in Figure 19. The sampling period used in this application is one second for all channels.

### [Figure 19]

We consider a fault in the most critical sensor in the installation, i.e. the boiler pressure sensor. Note that in nominal operation, boiler pressure is controlled between 7.8 and 8.2 bars through an on-off controller. We consider a system without FTC implementation, for which the steam pressure ( $P_7$ ) and temperature sensor ( $T_6$ ) readings are plotted in Figure 20 (a) and Figure 20(b), respectively. It is seen from these results that the boiler temperature drops during  $P_7$  failure, because the heater is automatically switched off as a safety measure.

### [Figure 20(a) & Figure 20(b)]

Fault accommodation is implemented by transiting to OM9a, i.e. controlling the heater by using temperature sensor ( $T_6$ ) and setting a new set point for the on-off controller to maintain the steam temperature between 169°C and 172°C, which corresponds to a steam pressure range between 7.7 to 8.4 bars. Measured steam pressure and temperature, when the fault tolerant control was activated in the supervision platform, are given in Figures 21(a) and 21(b), respectively.

### [Figure 21(a) & Figure 21(b)]

## 9. CONCLUSIONS

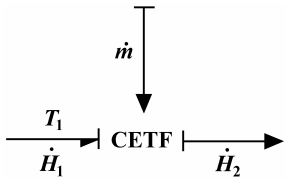
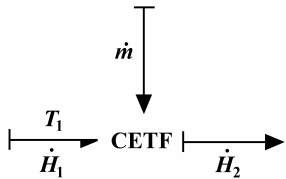
We have studied various developments made in the field of control engineering by applying bond graph modelling and observed that bond graph modelling is well suited to solve FDI and FTC problems in process engineering. Thereafter, we have applied these recent theories to develop FTC schemes for an academic example and shown that bond graph modelling is able to deal with wide ranging requirements of supervision systems. In the end, bond graph model is used to design FTC system for a steam generator installation and the experimental results from the process are presented.

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**Table 1. Definition of CETF**

Causal forms of CETF	Equation
	$\dot{H}_1 = \dot{m} \cdot c_p \cdot T_1$ $\dot{H}_2 = \dot{m} \cdot c_p \cdot T_1$
	$T_1 = \frac{\dot{H}_1}{\dot{m} \cdot c_p}$ $\dot{H}_2 = \dot{H}_1$

**Table 2. FSM for the academic example**

	$r_1$	$r_2$	$r_3$	$r_4$	$r_5$	$r_6$	$r_7$	$r_8$	$r_9$	$r_{10}$	$I_b$
PI	1	0	0	0	0	0	0	0	0	0	1
Pump	0	1	0	0	0	0	0	0	0	0	1
On-Off	0	0	1	0	0	0	0	0	0	0	1
Heater	0	0	0	1	0	0	0	0	0	0	1
Tank <sub>1</sub>	0	0	0	0	1	0	0	0	1	0	1
Tank <sub>2</sub>	0	0	0	0	0	1	0	0	0	1	0
V <sub>1</sub>	0	0	0	0	1	1	0	0	1	1	1
V <sub>2</sub>	0	0	0	0	0	1	0	0	0	1	0
L <sub>1</sub>	1	0	0	0	1	1	0	1	1	1	1
L <sub>2</sub>	0	0	0	0	1	1	1	1	1	1	1
L <sub>3</sub>	0	0	0	0	0	0	1	0	0	0	1
F <sub>1</sub>	0	0	0	0	0	0	0	1	0	0	1
T <sub>1</sub>	0	0	0	0	0	0	0	0	1	1	1
T <sub>2</sub>	0	0	0	0	0	0	0	0	0	1	1
Q <sub>p</sub>	0	1	0	0	1	0	0	0	1	0	1
U <sub>p</sub>	1	1	0	0	0	0	0	0	0	0	1
Q <sub>T</sub>	0	0	0	1	0	0	0	0	1	0	1
U <sub>O</sub>	0	0	1	1	0	0	0	0	0	0	1

**Table 3. Redundancies in the steam generator process**

Redundant device	Redundancy with?	Type of redundancy	Used in FTC of?
L9	L8	Direct/Hardware	Water level in boiler
L19	L18	Direct/Hardware	Condensate level
P14	P12	Direct/Hardware	Steam expansion system
P13	P16	Direct/Hardware	Steam expansion system
P15	P16	Direct/Hardware	Steam expansion system
T6	P7	Deduced/Functional	Boiler pressure
T5	P7	Deduced/Functional	Boiler pressure
T17	P16	Deduced/Functional	Steam expansion system

P27	(P16, L18)	Deduced/Functional	Condensate discharge
P2	P1	Material	Feed water supply
V1	V2	Direct/Hardware	Steam expansion system
V4	V3	Direct/Hardware	Condensate discharge
V5	V3	Direct/Hardware	Condensate discharge

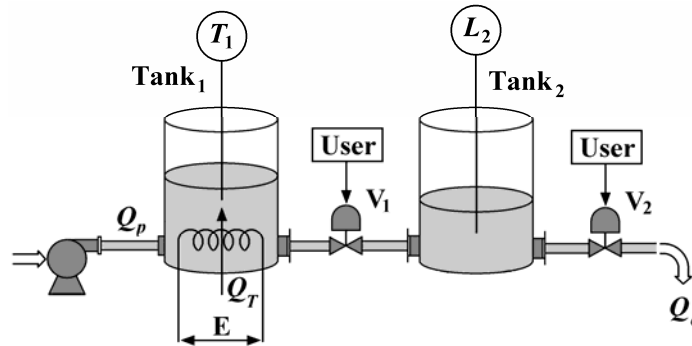


Figure 1. A two tank system

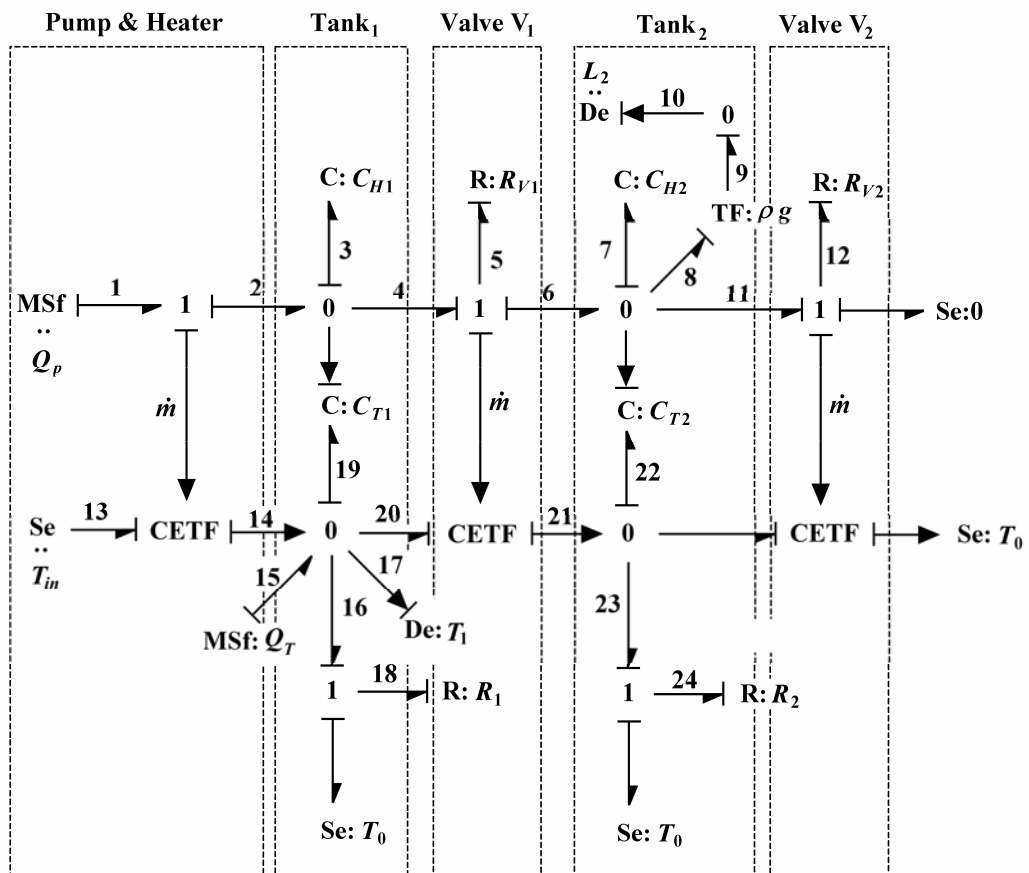


Figure 2. Bond graph model of the two tank system



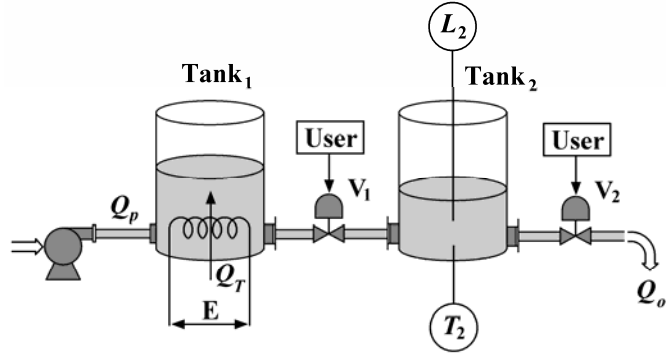


Figure 3. Modified sensor architecture in the two tank system

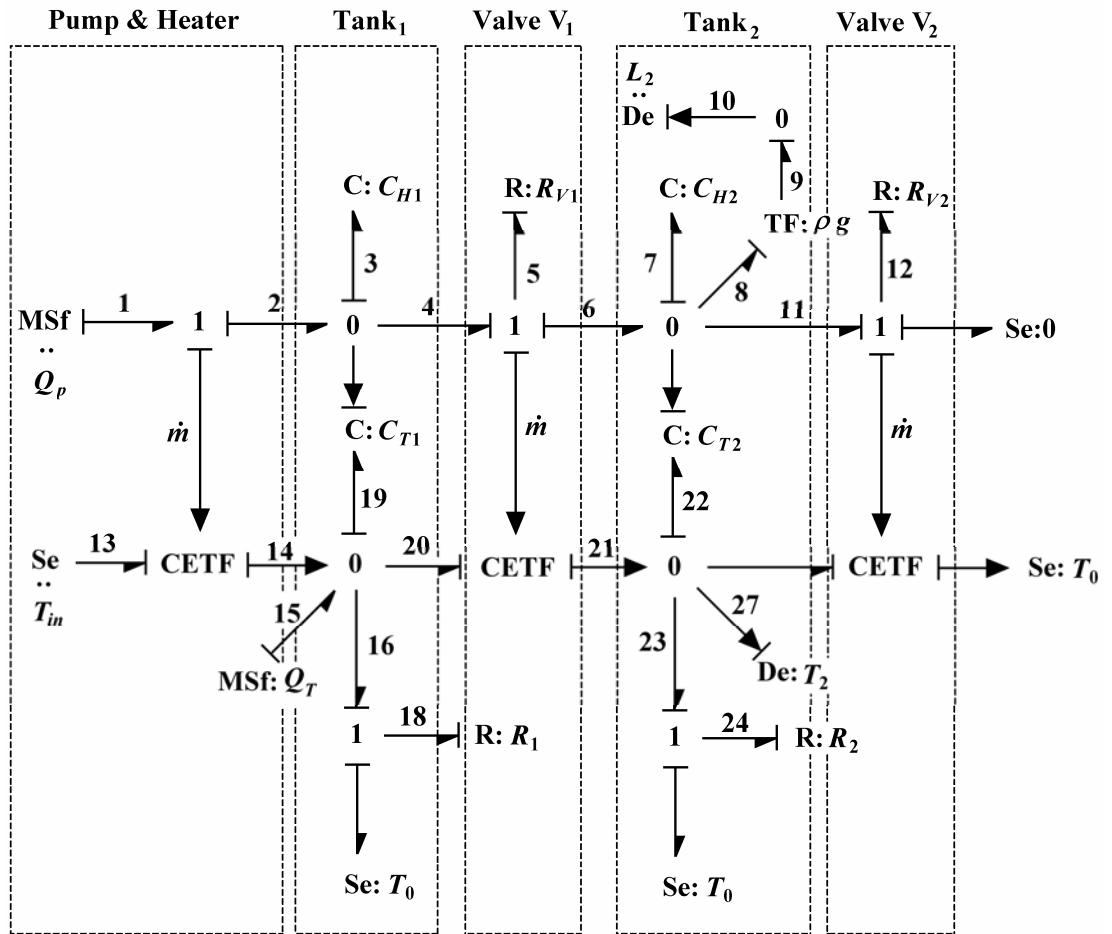


Figure 4. Bond graph model of two tank system with modified sensor architecture

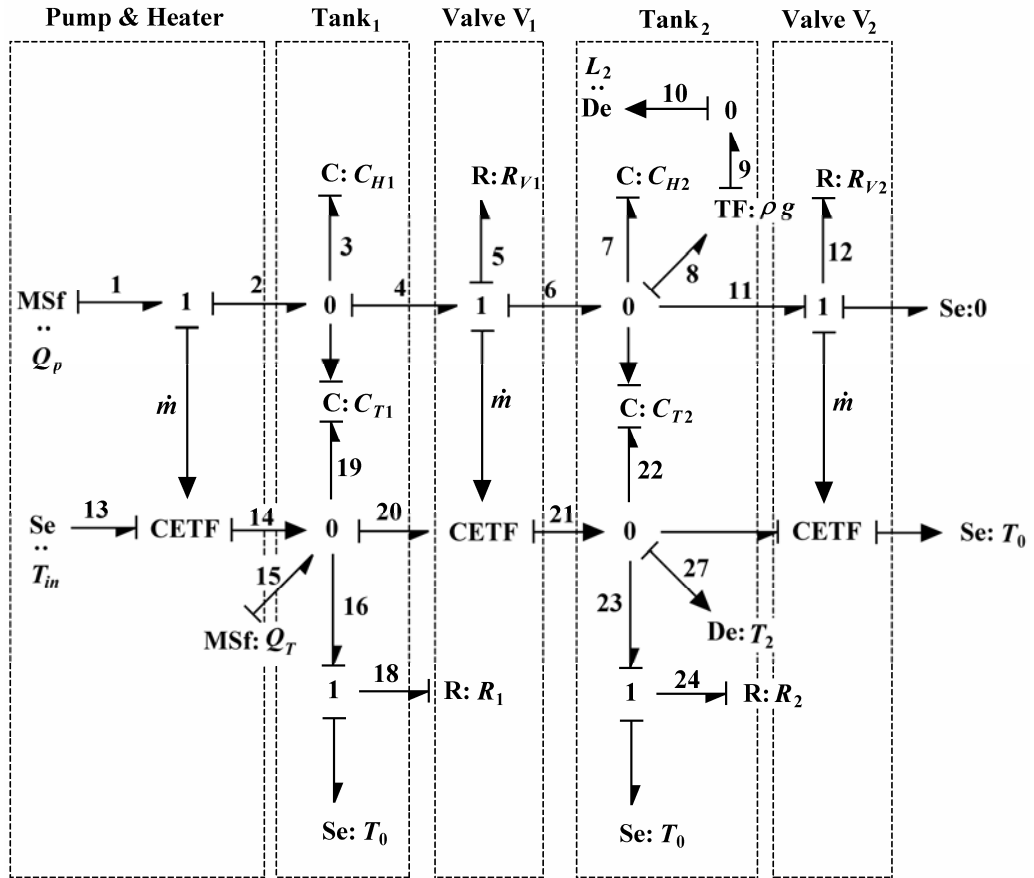


Figure 5. Bond graph model of two tank system in preferred derivative causality

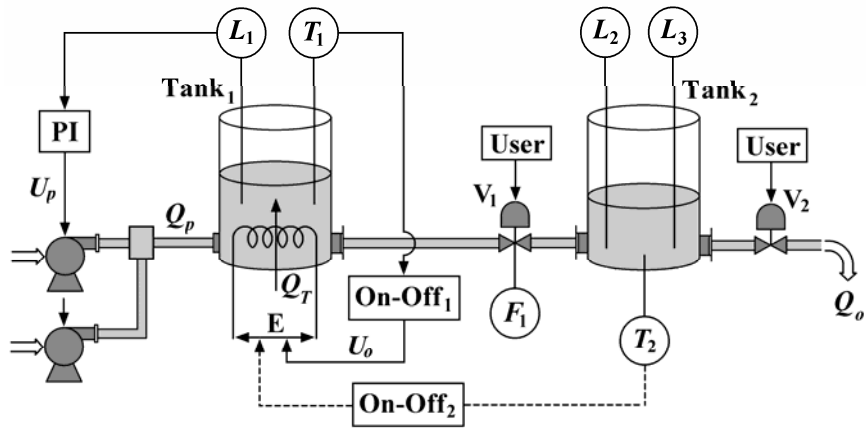


Figure 6. Two-tank system with redundant sensors and actuators

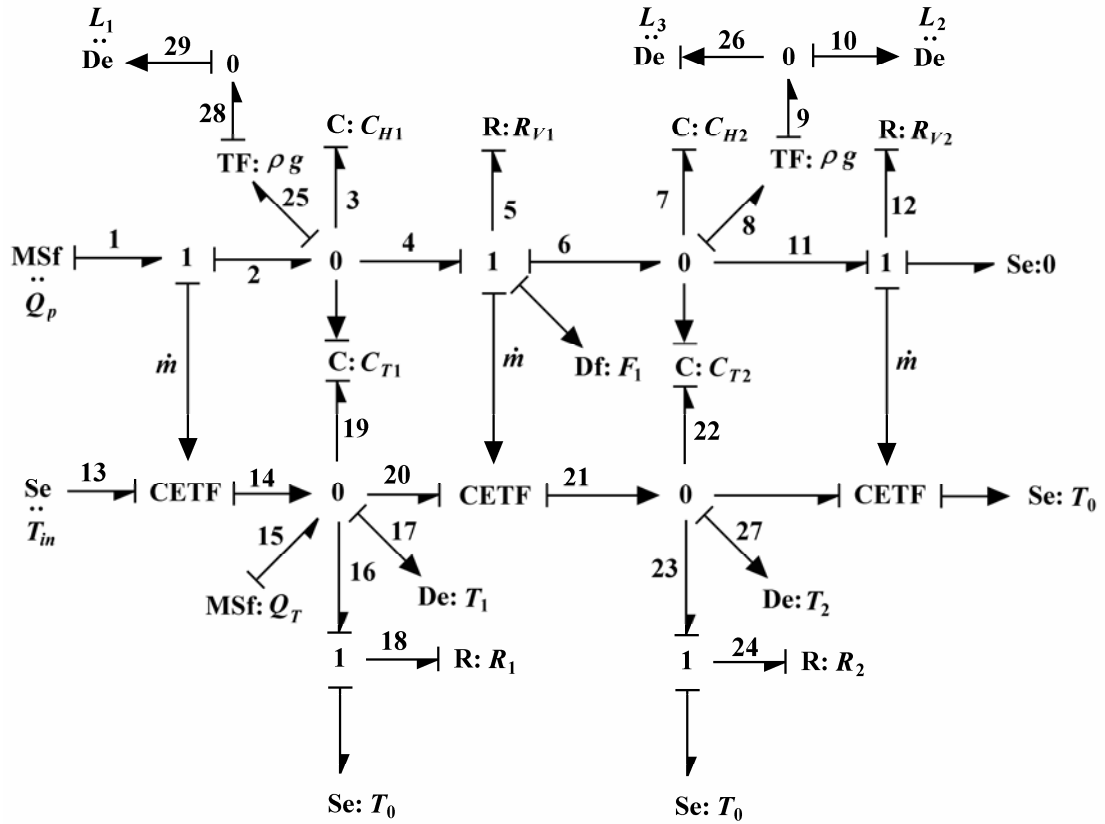


Figure 7. Bond graph model for the academic example in preferred derivative causality

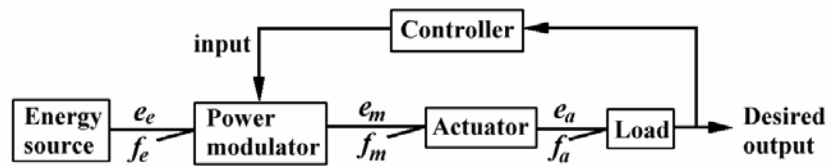


Figure 8. Word bond graph of a feedback actuated system

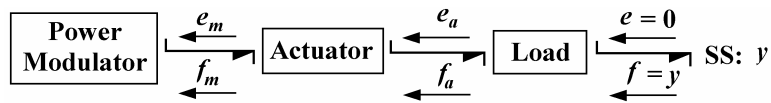


Figure 9. Inverse Model

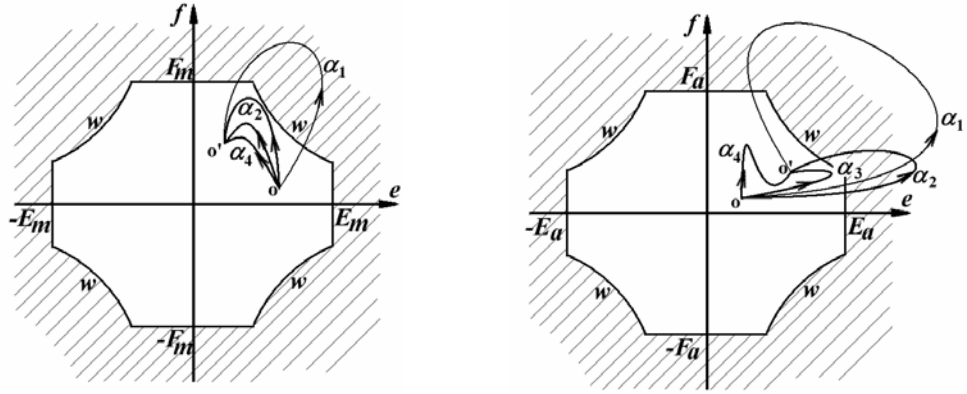


Figure 10. Trajectory of power variables in the constraint space

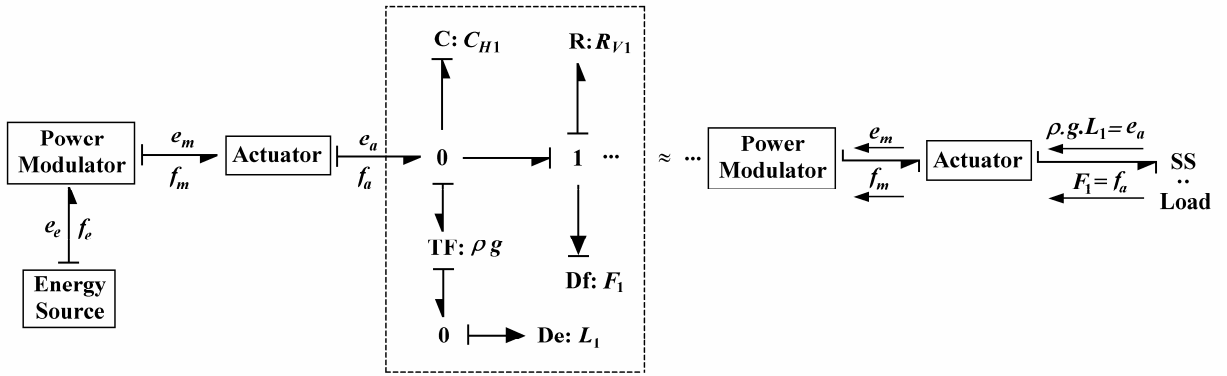


Figure 11. Actuator sizing for the academic example process

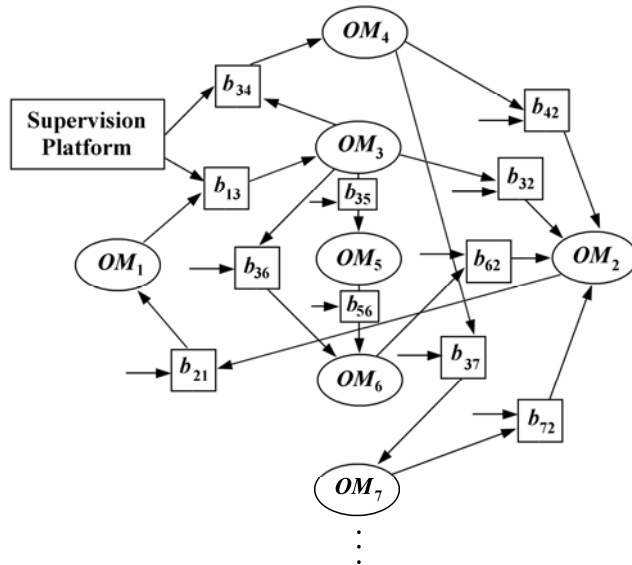
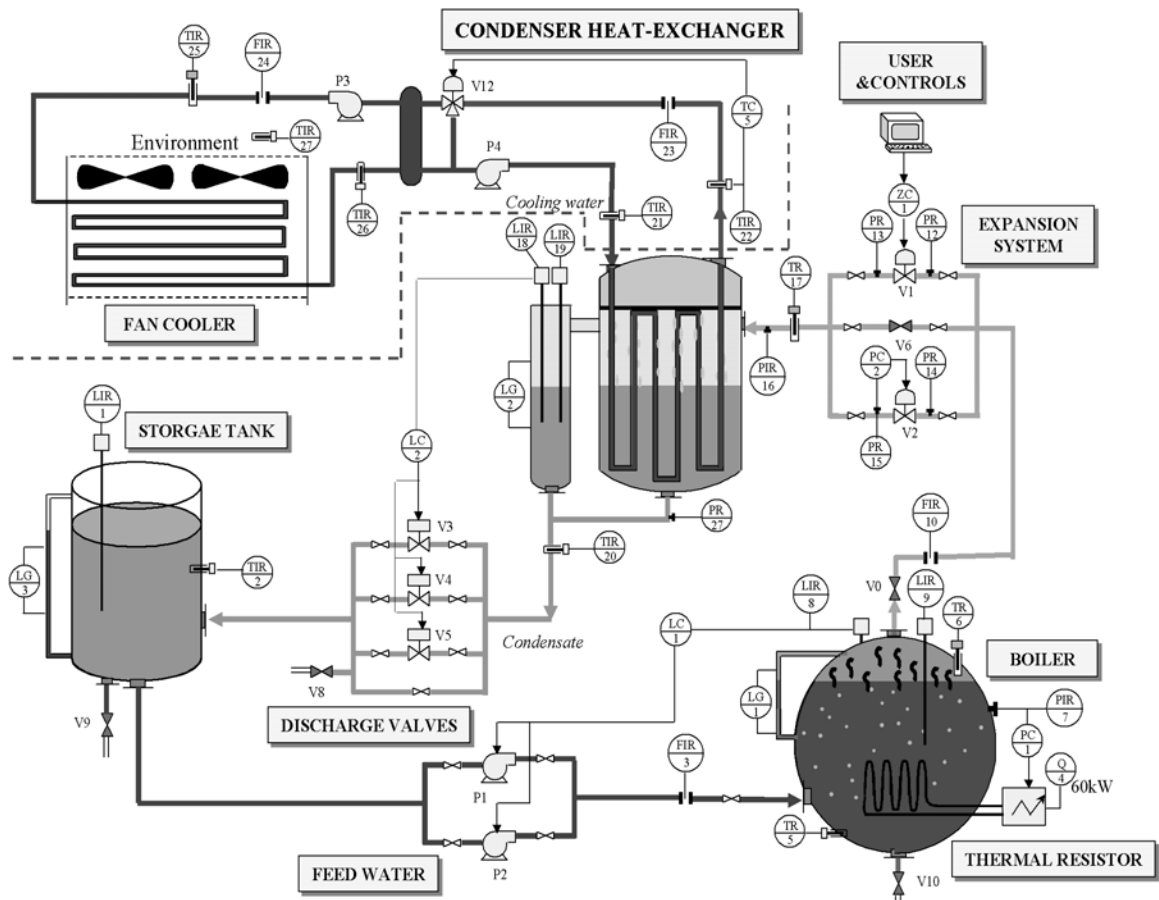


Figure 12. Operating mode management (in part) for the academic example process



**Figure 13.** The steam generator installation



**Figure 14.** Process and Instrumentation Diagram (P&ID) of the steam generator process

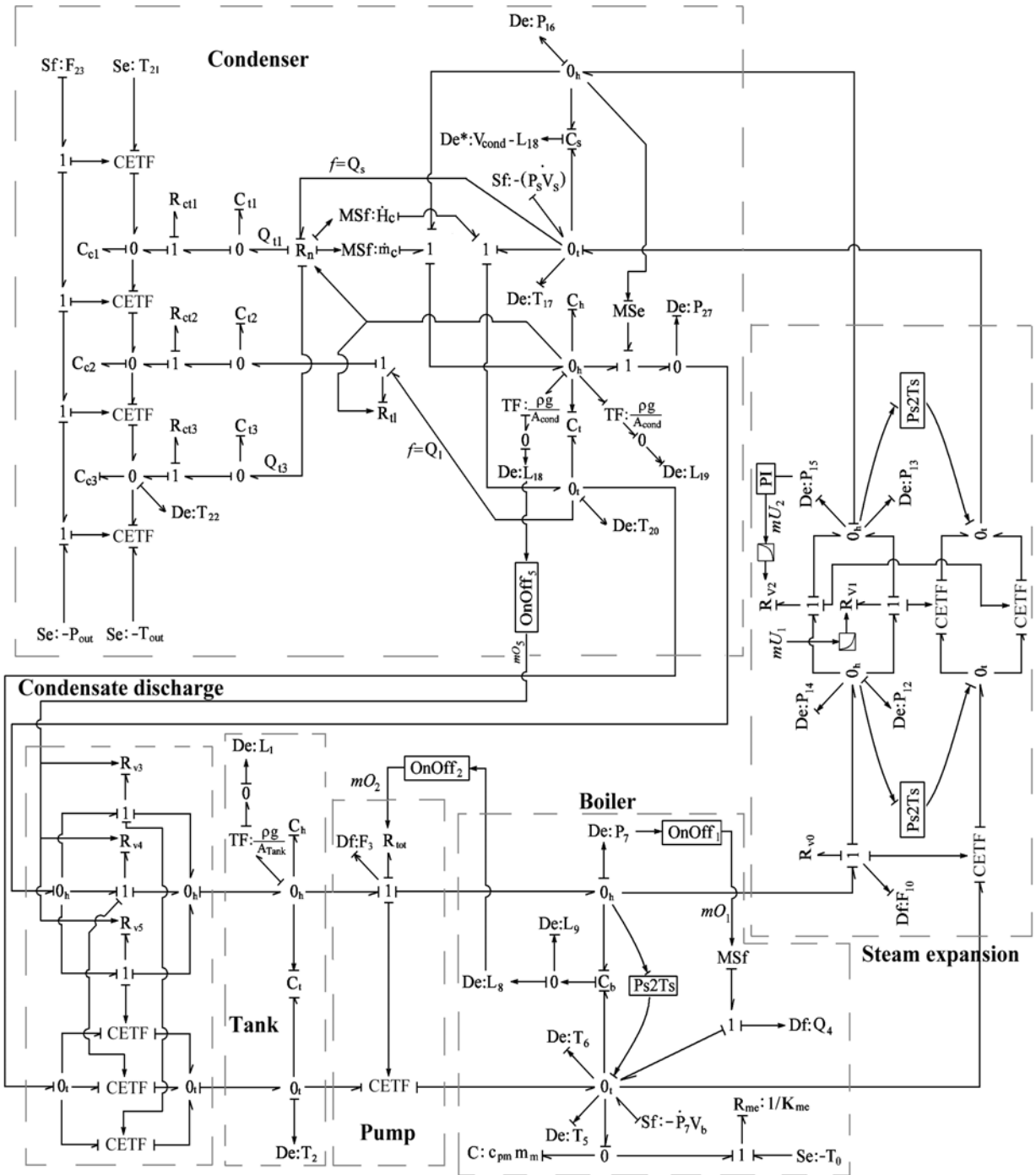
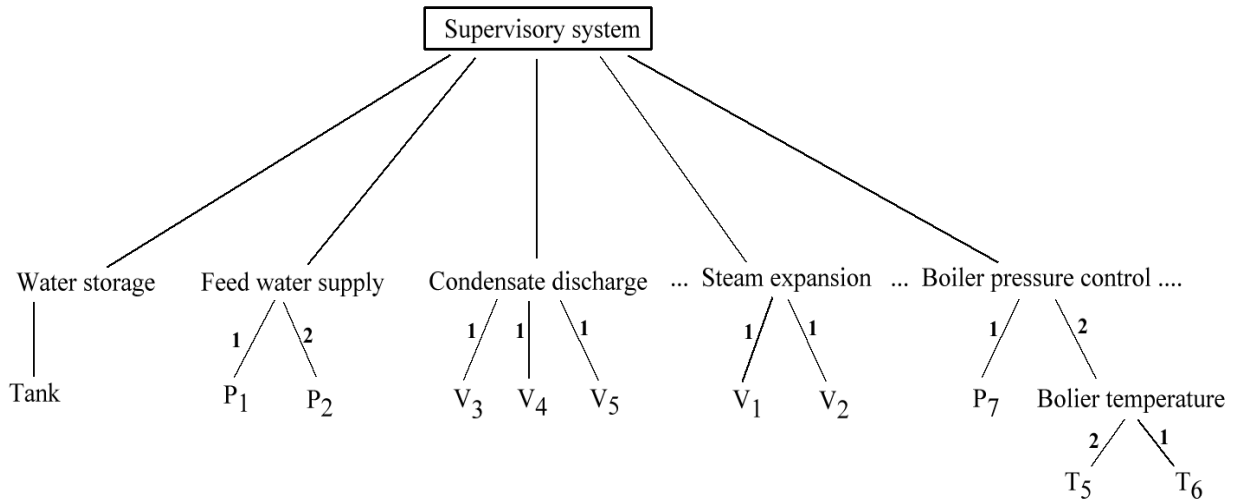
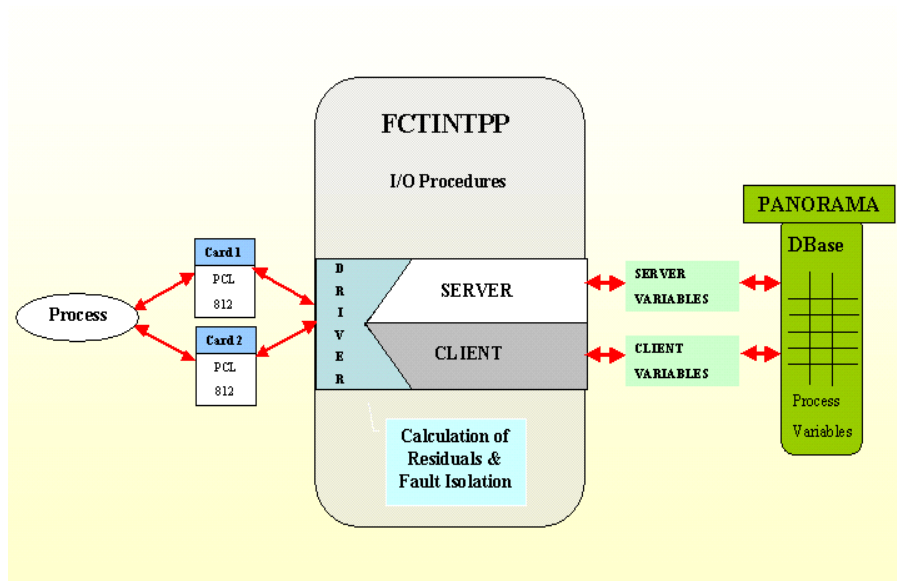


Figure 15. Bond graph model of the steam generator process in preferred derivative causality



**Figure 16.** Functional redundancy tree of the steam generator process



**Figure 17.** Data acquisition system

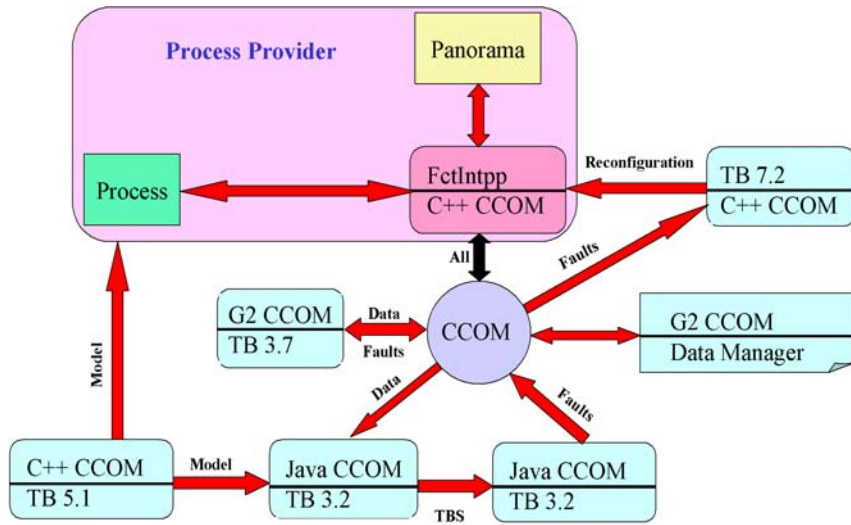


Figure 18. Toolbox integration in the steam generator process

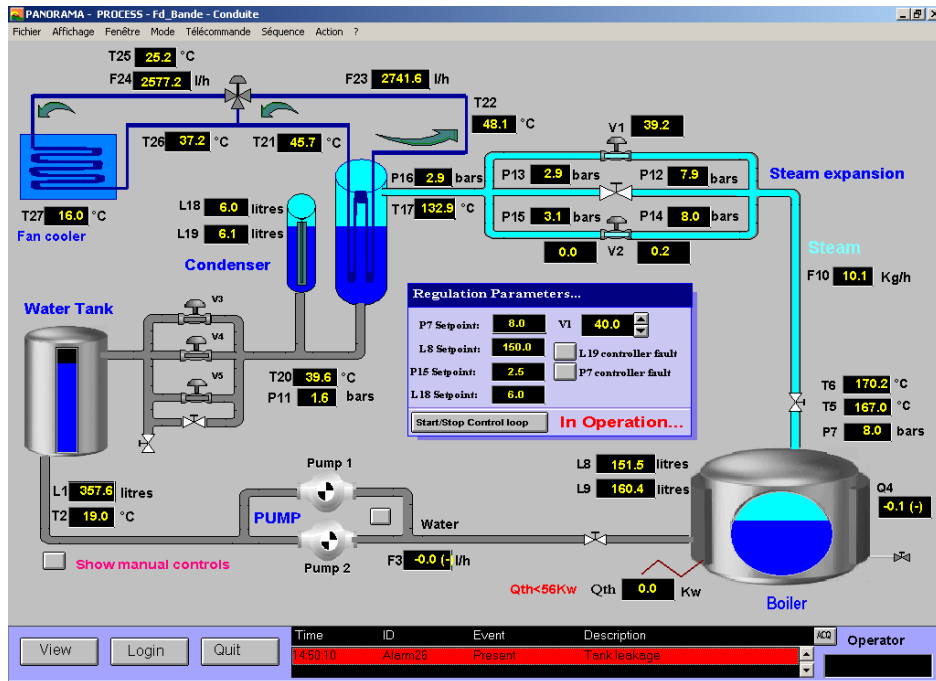
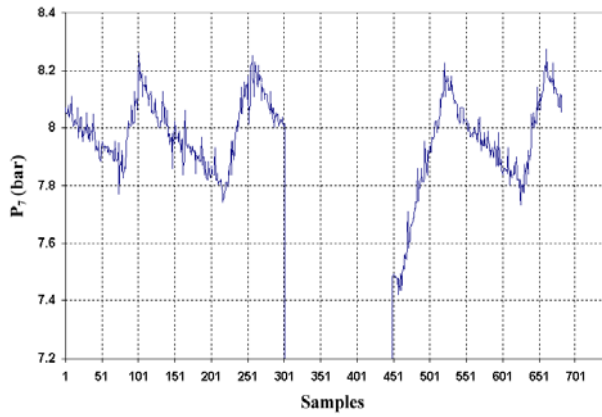
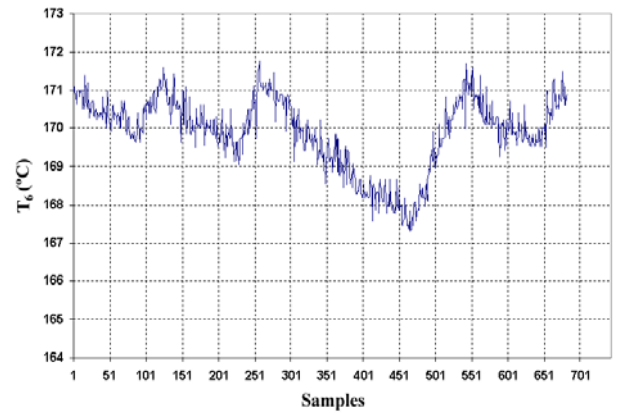


Figure 19. Panorama interface to monitor the steam generator process

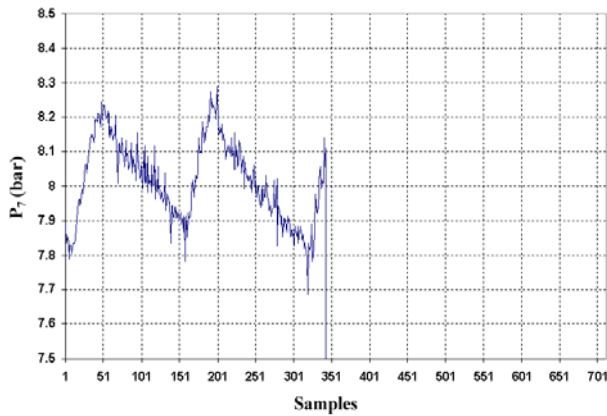




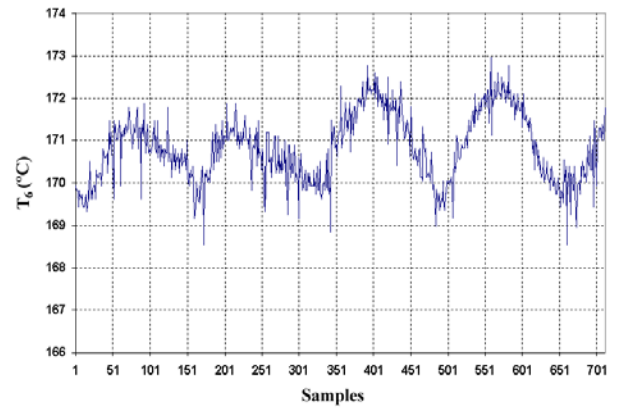
**Figure 20(a).** *Steam pressure sensor ( $P_7$ ) output.*



**Figure 20(b).** *Steam temperature sensor ( $T_6$ ) output.*



**Figure 21(a).** *Steam pressure sensor ( $P_7$ ) output.*



**Figure 21(b).** *Steam temperature sensor ( $T_6$ ) output after FTC implementation.*