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ICT and modelling methodologies for food safety and quality assurance in food production plants

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Abstract

In many food processing operations, product safety is still controlled by checking only the end product by microbiological and chemical methods. When unsafe food products are detected, part of the production has to be diverted and production process must be halted until the conditions causing unsafe product are diagnosed and eliminated. Fault diagnosis methods that can quickly identify the source causes that yield unsafe products would reduce the process down time and productivity loss. Monitoring and controlling processes are therefore crucial to ensure safety constraints, product quality, environment constraints and minimum cost simultaneously. Aim of this paper is to present a novel approach for modelling and monitoring an industrial food process to be used for detecting abnormal behaviour of the process.

Keywords: food plant modeling, fault detection, food engineering, food safety.

Introduction

In many unit operations in food industry, product safety is controlled by checking only the end product by chemical and microbiological methods. When unsafe food products are detected, part of the production has to be diverted and production process must be halted until the conditions causing unsafe product are diagnosed and eliminated. The major drawbacks associated with this approach are the time delay and the amount of product that generally has to be discarded. Consequently, the development of fault diagnosis methods, that can quickly identify the source that caused unsafe products, would reduce the process down time and productivity loss. When inadequacies of traditional food safety control, based on end product analysis, have been noticed, more effective ways to control the safety of food processing lines have been sought. The systematic and scientific approach called *Hazard Analysis and Critical Control Points* (HACCP) was first used in 1960s and it has been developed in the further 30 years (see e.g. Khandke & Mayes, 1998; Tokatli et al, 2005). Instead of checking only the properties of the end product, Critical Control Points (CCP) of the process are individuated and continuously monitored to prevent a possible major hazard in advance. Critical limits on specific measured variables (CCP) are used to ensure the safety of the product. Any measurement outside the critical limit indicates insufficient/inadequate treatment. This approach, in industry, is generally referred as *Statistical Quality Control* (SQC). A property is plotted on a control chart where appropriate limits are known (for example for microbial charge) or have been defined on the base of statistical analysis of previous good operation. The use of real time in-line data acquisition systems and/or analyzers allows to collect more frequent quality data, but still perform SQC. Unfortunately SQC does not guarantee that the process is in control, even if single measurements are within acceptable limits.

Early detection of upsets in the process variables can be performed by the so called *Statistical Process Control* (SPC) technique (Hayes *et al.*, 1997; Ittzés, 2000; Srikaeo *et al.*, 2005).

The reduction of the number of the investigated variables, that in some cases can be large, can be performed using multivariate projection methods (Kourti & MacGregor, 1995). According to these methods, among which Principal Component Analysis is one of most diffused, a small number of new variables are calculated.

Monitoring and controlling process are therefore crucial to ensure safety constraints, product quality, environment constraints and minimum cost simultaneously. Some methodologies have been introduced in this context for the analysis and control of manufacturing processes. *Process analytical technology* is technique recently proposed by Kourti (Kourti, 2006) and it is based on timely measurements during processes of critical quality parameters and performance attributes of raw and in-process materials and processes to assure acceptable end product quality at the completion of the process.

In this paper, a model based approach to monitor an industrial food process and detect abnormal behaviour of the process variable is presented. Such anomalies can be caused by sensors/actuators failures (physical failure) or by an improper (e.g. excessive working load, properties of raw materials etc.) usage of the plant. The effectiveness of this method relies in the accuracy of the model that is used to simulate the process in healthy conditions. Section 2 of this paper undertake the problem of the development of the models in the case of plants operating on fluid products taking into account possible mass-flow discontinuities and thermal exchanges. The estimation of relevant entities, as e.g. flow rate, permanence time and temperature profiles, is carried out using numerical procedures that require the joint quantization of time and mass flow variables. The simulation is driven by the state of the plant (i.e. opening state of the valves, state of the motors, temperature of the service fluids etc). The nature of the model is necessarily hybrid since it accounts both continuous variables (e.g. temperature) and discrete events (e.g. motors on-off, valves openings etc.). This approach has some analogies with this adopted in Dabbene *et al.*, 2008 for the modelling and optimization of fresh-food supply chains.

Finally, Section 3 presents a fault detection structure which operates analysing discrepancies between measured and estimated variables and Section 4 reports some conclusions.

Model development

The first step in the development of a tool for the diagnosis of faults and/or quality loss in food production plants is to build a model to simulate the plant in healthy conditions. When considering plant operating on fluid products, the main difficulty in modelling is to manage the flow discontinuities that some devices, such as valves, can introduce.

The model of a plant can be constructed as the interconnection of distinct modules, hereafter referred as node, whose description is derived from mass and energy balances. The product flows through nodes which are typically responsible of specific unit operations such as heating, cooling, storage, filling etc.

Define as *continuous-flow node* a node that does not internally store any amount of product. For this kind of node, incoming and outgoing flow rates are always equal.

On the contrary, a *discontinuous-flow node* is able to temporarily store amounts of product, so that incoming and outgoing flow rates can differ. Examples of a discontinuous-flow node are batch evaporators, holding or buffer tanks etc. The permanence time of the product in these nodes is not constant and cannot be, in many case, deterministically determined.

Since model parameters need to be identified on the base of measurements on the plant, model components are hereafter introduced in the discrete time domain, assuming a sampling period Δt. Analogously, the mass flows also is quantized introducing Δ_q as smallest portion of product that can be held in a Δ_t time period. The whole amount M of product processed in a batch (e.g. a session or a working day) is divided in a number $n = M / \Delta_q$ of portions of product that will be individually tracked during the process. To each i-th portion of product, two state variables $T_i(k)$ and $p_i(k)$ are associated. $T_i(k)$ represents temperature, while $p_i(k)$ accounts for the node where the i-th lot of product is stored at time instant k.

The simulation of the plant can be carried on at two different levels of detail: a low level, where individual masses (portions) of product are singularly tracked and described and a high level, where a fluid approximation of the process is considered. In this case average or cumulative entities only, like the delivery of a pipe, the mass of product stored in a node, the mean temperature of the product in a tank etc. are considered.

The flow in a specific section of the plant is expressed by $\dot{m}(k)\Delta_q$ and represents the amount of product (kg) that flows in a Δt time period through the considered section.

In the follow, models of basic node, that will be combined and used to describe complex plants, are introduced.

Buffer tank

Consider, as a basic modelling element, the very simple discontinuous-flow node depicted in figure 1. It is constituted by a tank with an incoming stream $\dot{m}_1(k)\Delta_q$ and an outgoing flow $\dot{m}_2(k)\Delta_q\, q_2(k)$. The signal $q_2(k) \in \{0,1\}$ accounts for on-off state of the valve at time instant k, while $\dot{m}_2(k)\Delta_q$ represents the flow rate through the valve.

The high level mass balance of the node can be expressed as

$$\overline{M}_a(k+1) = \overline{M}_a(k) + (\dot{m}_1(k) - \dot{m}_2(k) q_2(k))\Delta_q \qquad (1)$$

where the state variable $\overline{M}_a(k)$ represents the mass of product stored in the node.

The flow rate $\dot{m}_2(k)\Delta_q$ can be expressed as

$$\dot{m}_2(k)\Delta_q = \begin{cases} 0 & \text{if } \overline{M}_a(k) = 0 \\ \overline{M}_a(k) & \text{if } \overline{M}_a(k) \le v_2(k)\Delta_q \\ v_2(k)\Delta_q & \text{if } \overline{M}_a(k) > v_2(k)\Delta_q \end{cases} \qquad (2)$$

where $v_2(k)\,\Delta_q$ is the nominal flow rate that can be either measured directly on the plant (e.g. with a flow-meter) or estimated, using, for example, overall mass-balances. Equation (2) takes into account the fact that, if the tank is empty (i.e. $\overline{M}_a(k) = 0$) then the flow $\dot{m}_a(k)\Delta_q q_a(k)$ is equal to zero, even if the valve is open (i.e. $q_2(k) = 1$).

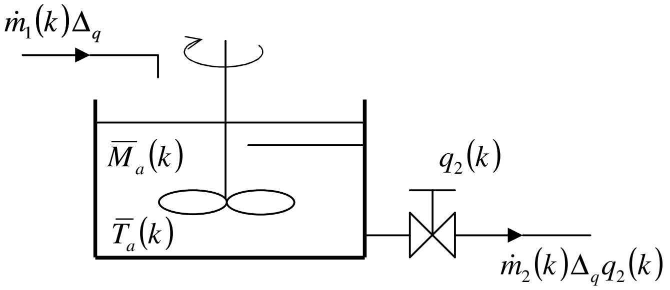

Figure 1. A simple stirred tank model

Analyzing the system from low level point of view, the permanence time of the product in this node cannot be exactly determined since new incoming product is continuously mixed with already stored product, so that it became undistinguishable. Permanence time can be estimated only in a stochastic sense, determining, for example, its average value. The approach proposed in this paper consists of modelling the tank as a First-In First-Out (FIFO) queue (see figure 2) where each element of the queue is constituted by a mass Δ_q of product and the server performs the simple task of deliver product at $\dot{m}_2(k)\Delta_q q_2(k)$ rate.

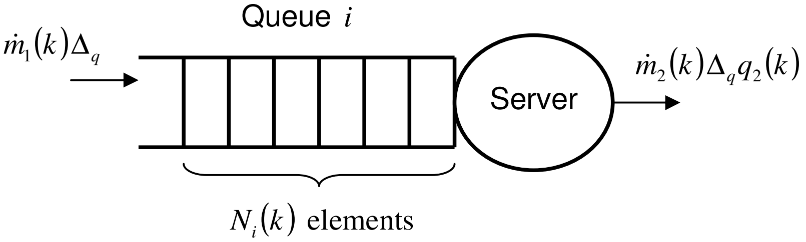

Figure 2. The queue model of a simple buffer tank

The service time of a specific portion Δ_q of mass of product represents its permanence time in the node. At each time instant k the position state $p_i(k)$ of all masses are updated by the queues.

The number of mass elements in the i-th node is $N_i(k)=\sum_{j=1}^{n}\delta_k(p_j(k),i)$, where $\delta_k(p_j(k),i)$ is the Kronecker delta and is equal to 1 if $p_j(k)=i$, 0 otherwise. The mass $\overline{M}_i(k)$ at time instant k is $\overline{M}_i(k)=N_i(k)\Delta_q$, while the average temperature $\overline{T}_i(k)$ in the node is

$$\overline{T}_i(k+1)=\frac{\sum_{j=1}^{n}\delta_k(p_j(k),i)T_j(k)}{N_i(k)} \tag{3}$$

Since the product in the tank is continuously mixed, we assume that each new incoming mass Δ_q in the node achieves the thermal equilibrium in Δ_t time interval, i.e.

$$T_i(k)=\sum_{j=1}^{n}\delta_k\left(p_i(k),j\right)\overline{T}_j(k) \tag{4}$$

Rewriting $T_i(k+1)$ in a recursive form, combining equations (3) and (4), it results

$$T_i(k+1)=\frac{1}{N_{p_i(k)}(k)}T_i(k)+\frac{\sum_{j=1,\ j\neq i}^{n}T_j(k)\delta_k\left(p_j(k),p_i(k)\right)}{N_{p_i(k)}(k)} \tag{5}$$

Buffer tank with two incoming streams

Consider, for this case, a stirred tank with two incoming streams $\dot{m}_1(k)\Delta_q$ and $\dot{m}_2(k)\Delta_q$ and an outgoing flow $\dot{m}_3(k)\Delta_q\,q_3(k)$, as reported in figure 3. Again the signal $q_3(k)\in\{0,1\}$ accounts for on-off state of the valve.

The mass balance of the node simply modifies in

$$\overline{M}_a(k+1)=\overline{M}_a(k)+\left(\dot{m}_1(k)+\dot{m}_2(k)-\dot{m}_3(k)q_3(k)\right)\Delta_q \tag{6}$$

where the variable $\overline{M}_a(k)$ represents the mass of product stored in the node, where the flow rate $\dot{m}_3(k)\Delta_q$ can be expressed again as in (2). The temperature $\overline{T}_a(k)$ of any mass in the tank can be obtained as

$$\overline{T}_a(k+1)=\overline{T}_a(k)+\frac{\dot{m}_1(k)\Delta_q\left(\overline{T}_1(k)-\overline{T}_a(k)\right)+\dot{m}_2(k)\Delta_q\left(\overline{T}_2(k)-\overline{T}_a(k)\right)}{\overline{M}_a(k)+\dot{m}_1(k)\Delta_q+\dot{m}_2(k)\Delta_q} \tag{7}$$

Temperature of the single mass Δ_q can be obtained again using relation (4).

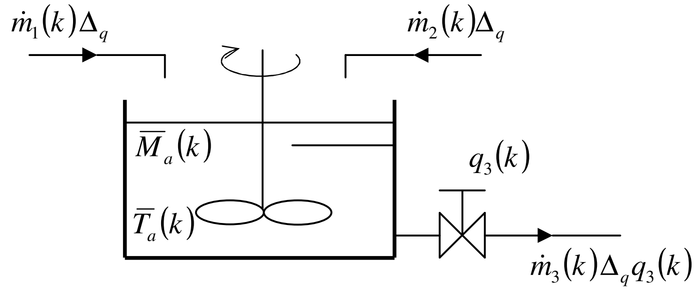

Figure 3. Model of a simple tank with two incoming streams

Two stirred tanks with an exchanging surface

This model structure can be used to represent simple heat exchangers where heat is exchanged by two fluids separated by a conductive wall. As can be seen in figure 4, this can be modelled by two simple tanks which are separated by a surface A through which a thermal flux ϕ, proportional to the heat transfer coefficient h, the difference of temperature in the two tanks and the surface itself A, is established. Mass balances are described rewriting equation (1) for each of the two tanks. At each time instant the temperature of each mass can be obtained according to the following procedure:

1. update the temperatures $\overline{T}_a(k)$ and $\overline{T}_b(k)$ of the tanks, considering the incoming streams $\dot{m}_1(k)\Delta_q$ and $\dot{m}_2(k)\Delta_q$ (see equation (3));
2. determine the thermal flow $\phi = hA\left(\overline{T}_a(k) - \overline{T}_b(k)\right)$
3. compute the temperatures $\overline{T}_a(k+1)$ and $\overline{T}_b(k+1)$ as

$$\overline{T}_a(k+1) = \overline{T}_a(k) - \frac{1}{\overline{M}_a C_{pa}} \phi \Delta_t, \quad \overline{T}_b(k+1) = \overline{T}_b(k) + \frac{1}{\overline{M}_b C_{pb}} \phi \Delta_t \tag{8}$$

   where C_{pa} and C_{pb} are the specific heat of the fluids in *a* and *b*;
4. determine the temperature of each mass contained in tank *a* and *b* (see equation (4)).

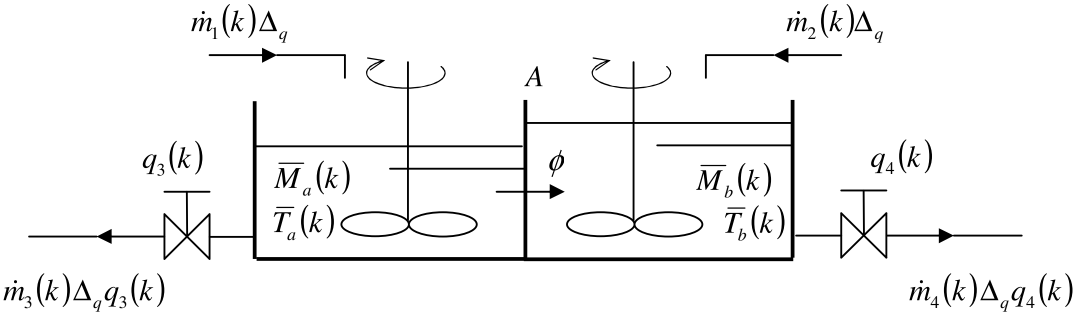

Figure 4. Two tanks with a thermal exchanging surface and incoming and outgoing streams

<u>*Continuous flow thermal exchanger*</u>

Continuous flow thermal exchangers, such as e.g. plate and tubular exchangers, can be approximated by a series of r simple exchangers, described in section 2.3. Figure 5 reports the scheme of a concurrent flow exchanger. Countercurrently flow exchanger can be analogously easily obtained. $\Delta\overline{T}_a(k)$ and $\Delta\overline{T}_b(k)$ represent temperature drops on each side of the exchanger, while $\dot{m}_a(k)\Delta_q q_a(k)$ and $\dot{m}_b(k)\Delta_q q_b(k)$ the flow rate of side a and b of the exchanger respectively. Temperatures can be obtained applying, for each stage, the procedure proposed in the previous section.

Fault diagnosis and detection

Aim of fault diagnosis methods is to individuate on-line the symptoms that indicate the beginning of a failure. This allows to foresee the fault recognition before the system breakdowns or, equivalently, the plant produces large amounts of unsatisfactory or unsafe product. Two distinct tasks can be performed: the detection of an abnormal behaviour of the plant and the individuation of the causes that have generated it.

The concept of a diagnostic system is constituted, as reported in figure 8, by a reference plant model which is used to generate, by simulation, estimated values that are adopted as reference output of a healthy plant. The difference between plant measured outputs and simulated reference outputs, performed by algebraic subtraction, provides the input for the diagnostic and fault detection modules. The simplest way to detect an abnormal behaviour consists of the evaluation, by means of statistical indicators, of the result of the subtraction. More sophisticate approaches have been presented in literature to detect a fault and to determine the causes (see e.g. Grimmelius et al, 1995). In this context, plant failures (e.g. a clogged up valve) are seen as additional inputs to the system. To guarantee that a specific plant failure could be detected from the system output, some conditions on controllability and observability properties of the system have to be satysfied.

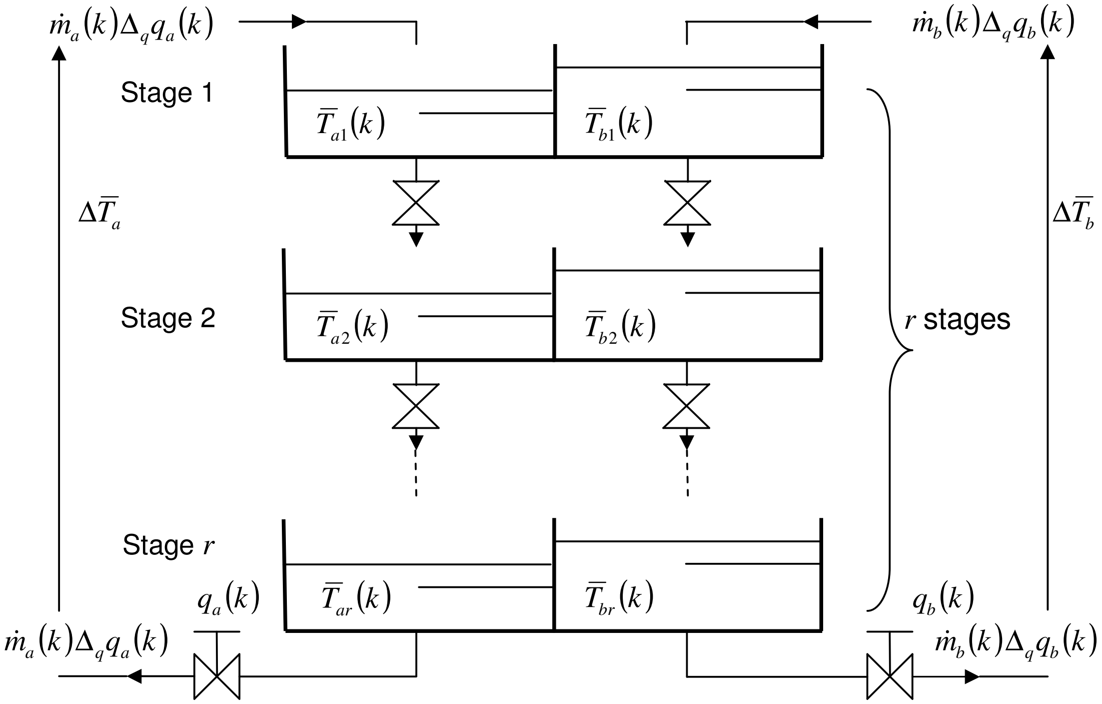

Figure 5. Model of a (continuous-flow) thermal exchanger

Conclusions

In this paper the problem of modelling and monitoring an industrial food process has been addressed. The proposed modelling methodology allows to cope with the case of discontinuous-flow plant which, to the best knowledge of the authors, have not been yet handled in literature, although most part of food plant operates in this condition. As discussed in the paper, a reliable model is the key element for fault detection systems that are able to early detect any plant failure that could compromise food safety and lead to quality breakdown.

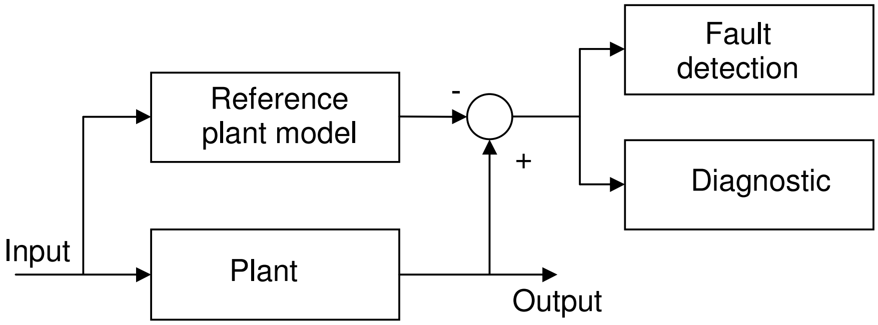

Figure 6. On-line fault detection and diagnosis

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