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Intuitionistic Fuzzy Logic in Generalized Net Model of an Advisory System for Yeast Cultivation On-line Control

Tania Pencheva

Centre of Biomedical Engineering, Bulgarian Academy of Sciences
105 Acad. G. Bonchev Str., 1113 Sofia, Bulgaria
e-mail: *tania.pencheva@clbme.bas.bg*

Abstract

The apparatus of Generalized Nets (GN) and Intuitionistic Fuzzy Sets (IFS) are here applied to a description of an advisory system for on-line control of yeast fed-batch cultivation. The advisory system and its GN realization appear as an expert system, comprising knowledge of well-trained operators of cultivation processes. Intuitionistic fuzzy logic is also implemented in the developed GN model in order to reflect the degree of uncertainty which is typical for measurements of biochemical variables. Developed GN model of the advisory system, with implemented intuitionistic fuzzy logic, is here applied for a fed-batch cultivation of *Saccharomyces cerevisiae*.

Keywords

Generalized nets, Intuitionistic fuzzy logic, Advisory system, Fed-batch process, Functional states, On-line control.

1 Introduction

Fermentation processes are characterized by a complicated structure of organization and interdependent characteristics, which determine their non-linearity and non-stationary properties. Many mathematical models of fermentation processes have been proposed but just a few have been used to optimize industrial plants. The common modelling approach is the development of an overall nonlinear model of fermentation processes that performs satisfactorily through the entire operating range. Unfortunately, this approach has a lot of disadvantages, namely a big number of parameters, which complicate the model identification and simulation and impossibility to reflect metabolic changes during the entire operating range and the parameter non-stationary. As an alternative, an increasingly popular multiple-model approach, and in particular – functional state modelling approach can be applied to cope with strongly nonlinear and time-varying systems, such as bioprocesses [5, 7, 10]. Using this approach the process is decomposed into different stages giving a simplified and transparent nonlinear model. When using functional state modelling approach, the step of the recognition of current functional state is an important task for development of an adequate model. Next, based on the current recognized functional state, advices for the further process control could be disposed to the users. Up to now GN have been used as a tool for the modeling of parallel processes in several areas [1÷3] – economics, transport, medicine, computer technologies, and so on. The apparatus of GN has been successfully applied also for modeling and control of fermentation processes [8, 11÷16]. The theory of GN permits on-line tracking of all process variables, included in the GN model, which cannot be done when the process is described with differential equations [16]. The use of GN for the description of cultivation processes affords the opportunities for on-line control, for searching optimal conditions for the fermentation, for process of learning on the basis of experimental data and for control on the basis of expert systems. Such advisory (expert) system has been developed for on-line control of fed-batch cultivation of *S. cerevisiae* [9]. Present work is devoted to the description of this advisory system applying the apparatuses of GN and intuitionistic fuzzy logic (IFL). Developed GN model of the advisory system with implemented IFL is further demonstrated for a fed-batch cultivation of *S. cerevisiae*.

2 An Advisory System for On-line Control of Yeast Fed-Batch Cultivation and its GN Model

The design of the advisory system for on-line control of a fed-batch cultivation of *S. cerevisiae* [9] is based on the preliminary developed system for recognition of functional states during the cultivation process [6]. As a test set, a fed-batch cultivation of *S. cerevisiae* performed in the *Institute of Technical Chemistry, University of Hannover, Germany* has been used in both systems [6, 9]. The functional states recognition system is built on the rules for recognition [17] and it is learned in such way to recognize all five functional states, although not all of them appear during the test experimental data set [6]. The advisory system is also learned for all five functional states giving users the advices which new functional state could be reached at the current time [9].

GN model described the advisory system for on-line control of yeast fed-batch cultivation [9] is developed [8]. This GN model is here shown (Fig. 1) for completeness and easer explanation of further research. GN model of the advisory system for on-line control of yeast fed-batch cultivation is based on the GN model described functional state recognition, developed in [12] for *E. coli* fed-batch cultivation. Presented GN model describes one more functional state (FS) than in [12], as well as designed as it has been designed as an expert system which is able to advise the user which new FS can be reached and what kind of control actions have to be taken.

Before to be developed the entire GN model, a small "parts" of the GN model have been considered [8]. Fig. 2a illustrates in principal how the advisory system works just for one functional state. Fig. 2b presents a part of GN model, describing which new functional state could be reached at the current moment of the cultivation. *Mixed oxidative state* (FS II according to Zhang et al. [17]) has been selected as a representative due to the maximum number of possible new states to which the process can switch.

Dotted lines in Fig. 2b present "a whole picture" of the possible transitions from FS II to other FS (all functional states names are according to Zhang et al. [17]). Just a short description of this small part of GN model is reported here. S denotes substrate concentration [g/l], E – ethanol concentration [g/l], and O_2 –dissolved oxygen concentration [%]. Subscript *crit* denotes their critical levels. If the token has been in place L_{13} with a characteristic "*mixed oxidative state* (FS II)" and:

- the user likes to switch the process to *first ethanol production state* (FS I), the $W^{I}_{13,18}$ is "the feeding in place L_{10} has to be increased in such way to reach $S > S_{crit}$ and the dissolved oxygen has to be kept $O_2 > O_{2crit}$"; the token will obtain a new characteristic "*first ethanol production state* (FS I)" and will appear in place L_{12} in the next cycle;
- the user likes to switch the process to *complete sugar oxidative state* (FS III), the $W^{III}_{13,18}$ is "ethanol should not be available in place L_7, substrate has to be kept $S \leq S_{crit}$ and dissolved oxygen has to be kept $O_2 \geq O_{2crit}$"; the token will obtain a new characteristic "*complete sugar oxidative state* (FS III)" and will appear in place L_{14} in the next cycle;

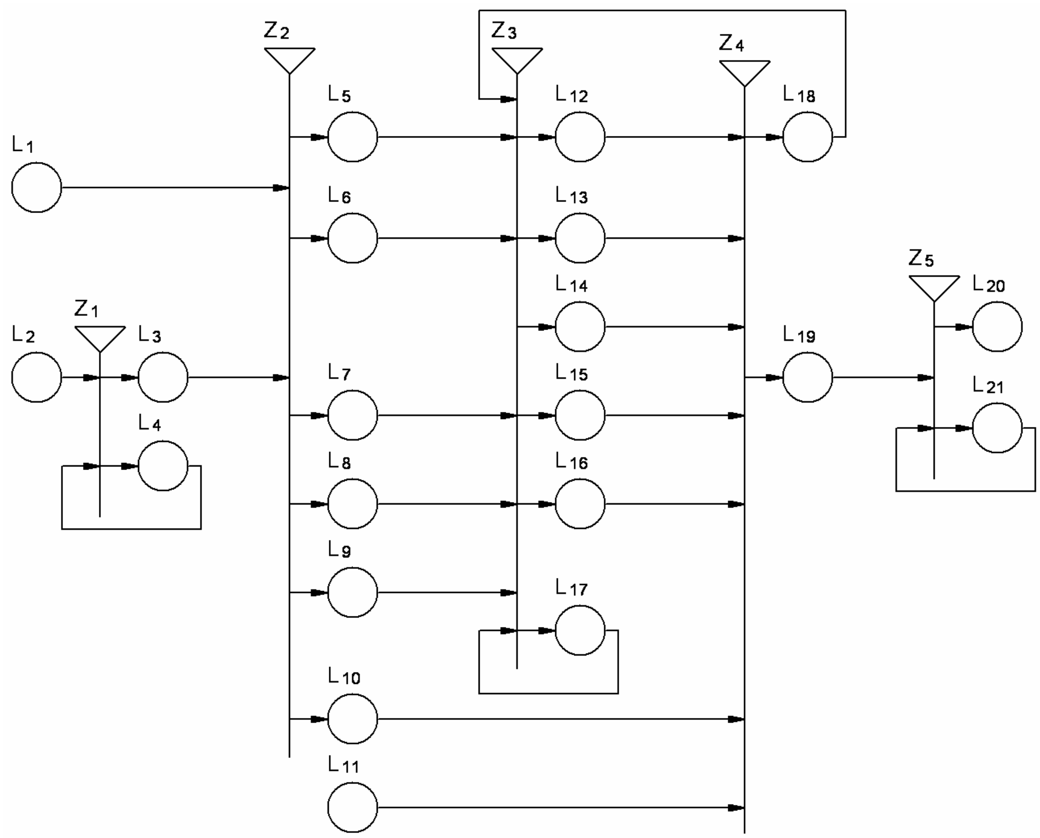
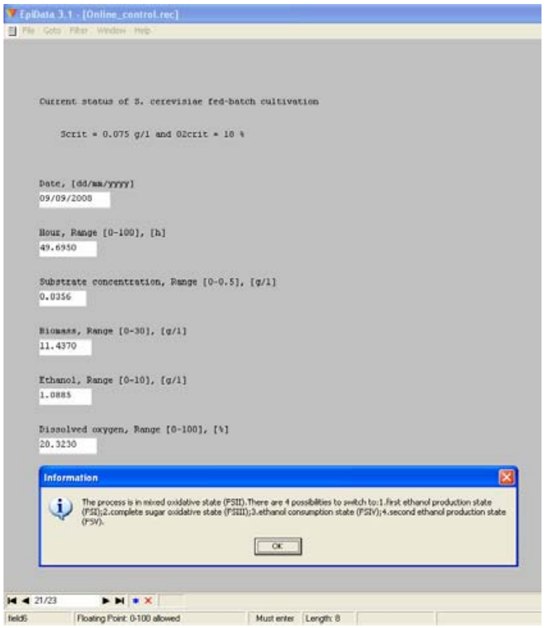


Fig. 1 GN model of an advisory system for on-line control of yeast fed-batch process [8]



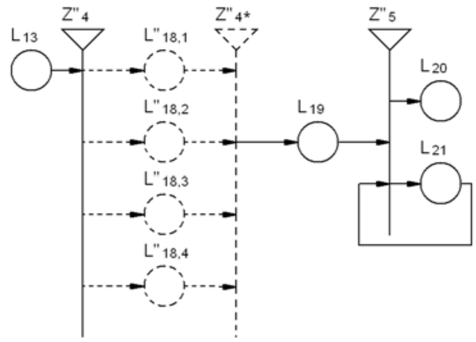


Fig. 2 *Mixed oxidative state* (FS II)

a) the response of the advisory system *b) a part of GN model*

- the user likes to switch the process to *ethanol consumption state* (FS IV), the $W^{IV}_{13,18}$ is "substrate should not be available in place L_5 (caused by lack of feeding solution in place L_4 or very fast growth of the yeast), and the dissolved oxygen has to be kept $O_2 \geq O_{2crit}$"; the token will obtain a new characteristic "*ethanol consumption state* (FS IV)" and will appear in place L_{15} in the next cycle; the process switches to batch mode;
- the user likes to switch the process to *second ethanol production state* (FS V), the $W^{V}_{13,18}$ is "substrate has to be kept $S \leq S_{crit}$, the aeration in place L_{11} has to be decreased in such way to reach $O_2 < O_{2crit}$ and ethanol should be available in place L_7"; the token will obtain a new characteristic "*second ethanol production state* (FS V)" and will appear in place L_{16} in the next cycle.

Further, when the whole GN model of the advisory system is presented, all "parts of GN model" from different FS are combined for a common description. In this way the user is advised for the possibilities which new functional state can be reached and what kind of control actions have to be taken in each of all possible five functional states.

3 Implementation of Intuitionistic Fuzzy Logic into GN Model

The Intuitionistic Fuzzy Sets (IFS) are defined as extensions of the ordinary fuzzy sets [4]. All results which are valid for the fuzzy sets can be transformed here. Also, all researches, for which the apparatus of the fuzzy sets can be used, can be described in the terms of the IFS.

Let a set E be fixed. An IFS A in E is an object of the following form:

$$A = \{<x, \mu_A(x), \nu_A(x)>| x \in E\}, \quad (1)$$

where functions $\mu_A : E \rightarrow [0, 1]$ and $\nu_A : E \rightarrow [0, 1]$ define the degree of membership and the degree of non-membership of the element $x \in E$, respectively, and for every $x \in E$:

$$0 \le \mu_A(x) + \nu_A(x) \le 1 \quad . \tag{2}$$

Let for every $x \in E$

$$\pi_A(x) = 1 - \mu_A(x) - \nu_A(x) \quad . \tag{3}$$

Therefore, function π_A determines the degree of uncertainty.

For the application of functional state modelling approach to fermentation processes, one of the most important steps is the reliable measurement of substrate, dissolved oxygen and ethanol concentrations. The rules for recognition of certain functional state are bound to current values of concentrations of S, O_2 and sometimes E at the current moment of the cultivation. The current state of the process is identified based on the relations between measured values of S and O_2 and their critical values, as well as from availability/non-availability of ethanol in the broth. Considered here *mixed oxidative state* (FS II) is characterized with $S \le S_{crit}$, $O_2 \ge O_{2crit}$ and availability of ethanol in the broth. That is why the accuracy of S and O_2 measurements is essential. In the fermentation processes it is very difficult to be determined whether a current measurement of a variable is a "truth" value or it is a "noise" value. That is why the critical values of S and O_2 are not considered as crisp values but they belong to the predetermined interval depending on the considered process. Let it is assumed that: $Y = [S, O_2, E]$ is the vector of process variables; μ_i^Y is the degree of appearance of the desired variable value from the vector Y at the i^{th} moment of time; ν_i^Y is the degree of appearance of the variable value from the vector Y at the i^{th} moment of time outside the predetermined interval, and π_i^Y is the degree of uncertainty. Let it is assumed also that the low boundary of the interval is $Y_{crit_{\min}}$ and the upper boundary is $Y_{crit_{\max}}$. Taking into account the error measurement, Δ, the following membership functions are defined:

- for substrate:

$$\mu_i^S : S_i \le S_{crit} + \Delta \tag{4}$$

$$\nu_i^S : S_i > S_{crit} - \Delta \tag{5}$$

$$\pi_i^S \text{, according to Eq. 3, is } \pi_i^S = 1 - \mu_i^S - \nu_i^S \tag{6}$$

- for dissolved oxygen:

$$\mu_i^{O_2} :\ O_2 \ \ge\ O_{2_{crit}} - \Delta \tag{7}$$

$$\nu_i^{O_2} :\ O_2 \ <\ O_{2_{crit}} + \Delta \tag{8}$$

$$\pi_i^{O_2} \text{, according to Eq. 3, is } \pi_i^{O_2} = 1 - \mu_i^{O_2} - \nu_i^{O_2} \tag{9}$$

- for ethanol:

$$\mu_i^E : E_i > 0 + \Delta \tag{10}$$

$$\nu_i^E : E_i < 0 - \Delta \tag{11}$$

$$\pi_i^E \text{, according to Eq. 3, is } \pi_i^E = 1 - \mu_i^E - \nu_i^E \tag{12}$$

Then, each moment of the cultivation process is bound with measurements of the process variables $\langle S_i, O_{2_i}, E_i \rangle$. Membership functions, connected to each moment and each process variable measurement are $\left\langle \mu_i^S, \nu_i^S; \mu_i^{O_2}, \nu_i^{O_2}; \mu_i^E, \nu_i^E \right\rangle$. Therefore the following prognoses for the identification of current functional state could be considered:

- strong optimistic prognosis:

$$\left\langle A, B \right\rangle = \left\langle \mu_i^S + \mu_i^{O_2} + \mu_i^E - \mu_i^S.\mu_i^{O_2} - \mu_i^{O_2}.\mu_i^E - \mu_i^S.\mu_i^E + \mu_i^S.\mu_i^{O_2}.\mu_i^E, \nu_i^S.\nu_i^{O_2}.\nu_i^E \right\rangle$$

- optimistic prognosis

$$\left\langle A, B \right\rangle = \left\langle \max\left(\mu_i^S, \mu_i^{O_2}, \mu_i^E\right), \min\left(\nu_i^S, \nu_i^{O_2}, \nu_i^E\right) \right\rangle$$

- average

$$\left\langle A, B \right\rangle = \left\langle \frac{\mu_i^S + \mu_i^{O_2} + \mu_i^E}{3}, \frac{\nu_i^S + \nu_i^{O_2} + \nu_i^E}{3} \right\rangle$$

- pessimistic prognosis

$$\left\langle A, B \right\rangle = \left\langle \min\left(\mu_i^S, \mu_i^{O_2}, \mu_i^E\right), \max\left(\nu_i^S, \nu_i^{O_2}, \nu_i^E\right) \right\rangle$$

- strong pessimistic prognosis

$$\left\langle A, B \right\rangle = \left\langle \mu_i^S.\mu_i^{O_2}.\mu_i^E, \nu_i^S + \nu_i^{O_2} + \nu_i^E - \nu_i^S.\nu_i^{O_2} - \nu_i^{O_2}.\nu_i^E - \nu_i^S.\nu_i^E + \nu_i^S.\nu_i^{O_2}.\nu_i^E \right\rangle$$

Formulated, based on the intuitionistic fuzzy logic, prognoses for the recognition of considered here *mixed oxidative state* (FS II) allow taking into account the measurement errors and noise influence, which are typical for all kind of measurements.

4 Conclusion

Intuitionistic fuzzy logic is implemented into the GN model described the advisory system for on-line control for fed-batch cultivation of *S. cerevisiae*. In this investigation the most representative state – *mixed oxidative state* (FS II according to Zhang et al. [17]) is considered, due to the maximum number of possible new states to which the process can switch. Implementation of IFL to all – concerning Zhang et al. [17] five functional states will allow to be reflected the degree of uncertainty when fermentation process variables are measured. The application of intuitionistic fuzzy logic leads to the significant decrease of the measurement error and noise influence. In such way designed advisory system and its GN model with implemented intuitionistic fuzzy logic could be of a high efficiency for on-line control and optimal carrying out of cultivation processes.

Acknowledgements

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