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# Qualitative interval (or fuzzy) simulation of complex continuous processes: Fitting information availability and accuracy requirements

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## ABSTRACT

The objective of this paper is to show through a real-world application why qualitative methods based on interval (or fuzzy) arithmetic with strong properties concerning soundness and completeness are adequate for modeling complex continuous processes. Firstly, we discuss modeling characteristics of such an important class of physical systems that includes chemical, nuclear, siderurgical and other industrial processes. On one hand, although it is almost always impossible to define numerical models for complex processes, it is usually possible to define boundaries (intervals) for the system parameters. On the other hand, some precision for the simulations is always required. We show that only interval (or fuzzy) based methods (and not pure numerical or qualitative methods) are adequate. Besides, for the effective use of such methods, soundness and completeness properties are of great importance. Secondly, in order to justify our claims, we present the successful application of QFSIM, a particular fuzzy-based qualitative method, to model a complex siderurgical process at CST "Companhia Siderurgica de Tubarao", a Brazilian-Japanese company located in Vitoria-Brazil.

# 1. INTRODUCTION

The goal of this paper is to show through a real-world application why qualitative methods based on interval (or fuzzy) arithmetic with strong properties concerning soundness and completeness are adequate for modeling complex continuous processes such as chemical, nuclear, siderurgical and other industrial processes. Soundness and completeness are understood in this paper with respect to instantaneous values of variables.

The reported experience on numerous projects that includes the ESPRIT Project 2761 [8], the ESPRIT Project 844 [9] and the CEA Project [5] [3] applied to chemical processes, the ALLIANCE Project [2] applied to a nuclear process and the MMC Project [14] applied to a siderurgical process, highlights the basic characteristics for the modeling of complex continuous processes :
1) Information Availability : Precise models are in most cases unavailable due to the complexity and the frequent experimental nature of such processes. Pure numerical methods are, that way, inadequate to model these processes. However, it is usually possible to define boundaries (intervals) for the system parameters.
2) Solution Accuracy Required : Due to the productivity, safety and reliability requirements, optimum operation has been essential. Most processes are controlled to work within operation ranges that tend to become narrower as requirements increase or more knowledge about the process is available. In That way, simulation methods that do not determine at least ranges of the possible values for the variables at a particular time (time point or time interval) are of less interest (pure qualitative simulation methods for example).

From the above discussions, interval or fuzzy (in this paper, the terms "interval" and "fuzzy" are interchangeable. In fact, fuzzy arithmetic generalises interval arithmetic) qualitative methods look adequate for modeling such class of physical systems. However, special care is to be taken regarding the soundness and completeness properties [7]. While an incomplete method may fail in predicting important behaviour (with drastic consequences in some cases), a method that produces too much spurious behaviours, for example opening too much the range of possibilities for a variable value or a time interval, is useless (too much false alarms when used to detect the crossing of a particular operating region, too much failures when used for fault detection in diagnosis [10], etc).

In order to justify our claims, we present the successful application of QFSIM [11][12], a fuzzy-based qualitative simulation, to model a complex siderurgical process at CST "Companhia Siderurgica de Tubarao" (a Brazilian-Japanese company located in Vitoria-Brazil) within the MMC Project [14].

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This paper is organized as follows: In section 2 we describe the CST Sintering Process. In section 3 we discuss the modeling characteristics of most complex continuous processes. QFSIM, one particular qualitative fuzzy simulation method is briefly presented in section 4. Section 5 shows the application of QFSIM to the CST Sintering Process. We close with discussions and concluding remarks.

## 2. THE CST COMPLEX SINTERING PROCESS

In this section we present the CST sintering process, the complex continuous process used throughout the paper as an example. The sintering process continuously produces sinter ore with various kinds of iron fine ore as the raw material and lime stone as the binder [4]. The process has two major goals. One is the stabilization of operation to produce uniformly grain-sized and strong sinter ore as the ferrous burden of blast furnace. Another is the optimization of the process to minimize the production cost under various conditions and processing throughout the whole iron works.

### 2.1 The Structural Description

In figure 2.1 we show the structural components of the sintering process, that are: the blending hoppers, the drum mixers, the surge hopper, the sinter bed, the ignition furnace, the wind boxes and the cooler. The blending hoppers keep the raw material that is mixed and granulated by the drum mixers and sent to the surge hopper. The granulated raw material in the surge hopper is fed across the sinter bed width and is ignited by the furnace. The material burns from the surface toward the bottom by the downward air flow through the wind boxes. The material is shifted by the sinter bed towards the cooler.

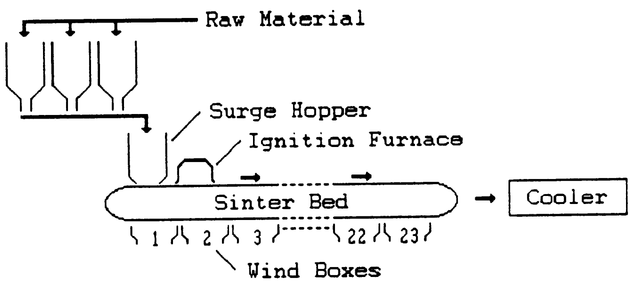


Fig. 2.1 - The Sintering Plant.

The goal of the operator is to control the sinter bed speed in order to maximize the productivity with safety. Too low speed causes low sinter production and quality while high speed can damage the equipment (burning material fed into the cooler can cause fire).

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## 2.2 The Operation Model

Even if process operators and engineers are directly interested in the sinter quality and productivity, such variables can not be directly analysed. They actually work on a set of observable variables related to the process variables of interest. Such relationships among observable and process variables can usually be defined due to the large experience of operators and engineers and are almost never precisely defined. We call such cognitive process model the "operation model". During the operation, the structural components are let aside and the main reasonings carried by operators and engineers are based on the operation model.

In the case of the CST sintering process, an observable variable called the burn through point "BTP" is the main variable to control. By experience, the operators are supposed to maintain the "BTP" in between 65 and 78%. The "BTP" below the lower boundary corresponds to a low sinter quality condition and a lost of productivity while the "BTP" above the higher boundary corresponds to very dangerous operation condition. The ideal is to keep it in between 70 and 75%.

Figure 2.2 illustrates a squelch of the operation model used by the operators and engineers to reason about the sintering plant. Basically, the "BTP" is influenced by the bed sinter speed "BSS", by the pressure on the wind box #6 "P106", and by the raw material humidity "UMI". The "P106" reflects the granularity of the raw material which is a non-observable variable. Another important observable variable used to guarantee safety is the burn through point temperature "TBTP". It is also influenced by "BSS", "P106" and "UMI". Regardless of the large number of sensors and thus observable variables, the actual cognitive operating model is only constituted by a small number of variables. Such important abstractions usually take place after years of experience with the process.

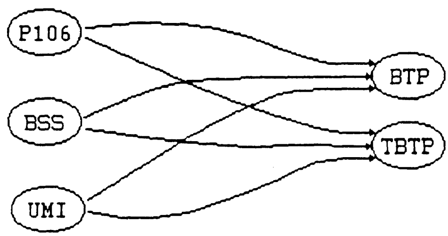


Fig.2.2 - The Sintering Process Causal Operation Model.

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## 3. CONTINUOUS PROCESSES MODELING CHARACTERISTICS

In this section we discuss the modeling characteristics of most complex continuous processes such as those of chemical, nuclear, siderurgical and other industrial plants, i.e. are the incomplete knowledge availability and the solution accuracy required.

### 3.1. Information Availability

Precise models of most complex systems are usually unavailable due to the complexity and the frequent experimental nature of such processes. As illustrated in the case of the CST sintering process, the variables of interest like the sinter quality are not directly observable variables. Such variables are monitored through related variables like the "BTP" or the "TBTP". The relationships among observable and non-observable variables, and even among the observable variables of the operation model are only barely known. The operators have only a scarce idea of such relationships. It is thus very complicated (if not impossible) to define precise models. Pure numerical methods are, in that way, inadequate for modeling such class of complex processes.

Besides, in some cases, the system parameters change depending on unknown phenomena. The point here is not that such parameters should be defined using intervals or qualitative values because of lack of knowledge, but that those parameters change according to unknown phenomena. They do not have unique values for all the operating conditions. For example, the model coefficients can significantly change with a strong change in the raw material quality which is a difficult variable to analyze. Pure numerical methods are definitely inadequate in such cases.

On the other hand, it is usually possible to define boundaries (intervals) for the system parameters. Engineers and operators have an important amount of knowledge about the process that includes the causal net among the operation model variables (which variables cause which variables) and a set of information about relationships, very often in terms of order of magnitude. For example when the pressure "P106" starts increasing fastly the "BTP" may also increase fastly in about 20 minutes. We used the qualitative term "fastly", but it is impressive how such terms always have a relationship to numbers in the monitoring of continuous processes. Such terms can not be defined precisely, as discussed in the last paragraph, but can usually be defined as intervals.

In the case of our experience in the CST sintering process, the set of information acquired from engineers and operators plus the information acquired from the analysis of the system behaviour made it possible to define a

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complete fuzzy model of the process. The methodology for such process knowledge acquisition is briefly described in section 5.

### 3.2. Solution Accuracy Required

Due to the actual productivity, safety and reliability requirements etc, optimum operation has been essential. Most processes are controlled to work within operating ranges that tend to become narrower as the requirements increase or more knowledge is available. Optimum operation is directly linked to numbers. In the case of the CST sintering process, it is ideal to keep the "BTP" in around 75%. The goal of our project itself is to be able to keep the "BTP" around this point. It is important to state that small deviations can be very significant to the process. For example, a "BTP" increase of around 3% when its value is at 75% correspond to a very dangerous operation region (can cause damage of the coolers and fire).

Thus, simulation methods that do not determine at least ranges of possible values for the variables at a particular time (time point or time interval) are of less interest (pure qualitative simulation methods for example). For example, it is not sufficient to know that the "BTP" may increase in the "future" because "P106" has increased. The optimization of the process control becomes possible as such predictions become more precise.

From the above discussions, interval or fuzzy qualitative methods look adequate for modeling such class of physical systems. However, special care is to be taken regarding the soundness and completeness properties [7]. On one hand, an incomplete method may fail in predicting important behaviours. For example, it could miss an increase of "TBTP" that could indicate the damage of the coolers and fire. On the other hand, a method that produces too much spurious behaviours, opening too much the range of possibilities for a variable value or a time interval is useless. The simulator could indicate for example that the "BTP" could be in between 65 and 75% at some time. How to use such information to control the process? Should the operator increase or decrease the "BSS" in order to control the "BTP"?

Our experience with fuzzy and interval simulator (see section 4) showed that special care is to be taken in what concerns the soundness and completeness properties of interval-based qualitative simulators.

## 4. QUALITATIVE FUZZY SIMULATOR

In this section we briefly present one particular qualitative fuzzy simulator called QFSIM [11][12]. QFSIM simulates piece-wise first, second and third order linear systems with qualitative fuzzy coefficients. It is inspired from numerical simulation methods, in particular the Euler Method.

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In our first attempt to fuzzy simulation, we extended the Euler Method to conventional fuzzy operators based on the Extension Principle [15]. This simulation produced too much spurious behaviours (it opened too much the intervals), mainly because of the strong interactivity among the variables involved in the simulation [13]. We then proposed two methods, namely the Extremities and the Discretization Method. The first one is complete but not sound, even though it produces much less spurious results than the method mentioned before. The second one is sound and it converges towards completeness as the discretization is refined. These methods are used to determine the set of possible variable values at each instant.

In figure 4.1 we show an example of the QFSIM Extremities Method to simulate the first order system $X' + kX = f(t)$ where k is the fuzzy value [0.2 0.3 0 0] and $f(t) = 10$ if $0 < t < 14$, $f(t) = -10$ if $t > 14$. A value $[a\ b\ \alpha\ \beta]$ is associated to a fuzzy quantity M with membership function $\mu M(u)$ defined as:

$\mu M(u) = 1$ if $a \leq u \leq b$
$\mu M(u) = 0$ if $u \leq (a - \alpha)$ or $u \geq (b + \beta)$
$\mu M(u) = \alpha^{-1} (u - a + \alpha)$ if $(a - \alpha) < u < a$
$\mu M(u) = \beta^{-1} (-u + b + \beta)$ if $b < u < (b + \beta)$
where $(a, b) \in \mathbb{R}$, $a \leq b$, $\alpha, \beta \geq 0$.

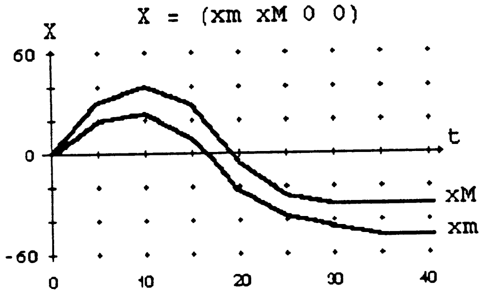


Fig. 4.1 - Fuzzy simulation of a first order system.

The main drawbacks of the Extremities and Discretization Methods are that the first is difficult to extend to higher order systems and the second is combinatorial when simulating piece-wise linear systems with several operating regions.

## 5. MODELING THE CST SINTERING PROCESS WITH QFSIM

Basically, the methodology to acquire the process information to model the CST sintering plant with QFSIM follows the steps below :
1) Determination of the significant observable variables i.e. the operation model variables. Example : "BTP", "TBTP", "P106", "UMI" and "BSS".
2) Determination of the causal net among such variables i.e. which variables cause which variables. For example, "BTP" is basically caused by "BSS", "P106" and "UMI".
3) Determination of the type of relationships among the variables. For example there is a piece-wise first order relationship with delay between "P106" and "BTP", and the delay is around 1150 second.
4) Determination and tuning of the fuzzy values for the system parameters for each operating region. We proceeded by first defining rough intervals for the parameters and then trying to refine them by analysing consecutive simulations. For example, the following values are the "fuzzy value" of the first-order coefficient of the first order relationship between "P106" and "BTP":

If BTP $<$ 70% => k = ( 9, 15, 0, 0 )
If 70% $\leq$ BTP $\leq$ 75% => k = ( 11, 14, 0, 0 )
If BTP $>$ 75% => k = ( 10, 12, 0, 0 )

Figure 5.1 shows part of the CST sintering process fuzzy operating model. In particular we show the relationship between "P106" and "BTP". We are not allowed to present the CST sintering process fuzzy model in details (industrial secret).

$$BTP'_{P106} + k \cdot BTP_{P106} = P106\,(t-\tau)$$

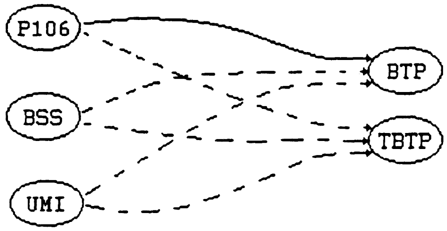


Fig. 5.1 - Part of the CST sintering process fuzzy model.

Figure 5.2 shows a QFSIM predicted behaviour (the two outer soft lines) and the measured behaviour (the inner line) for a duration of 8 hours approximately. It can be seen from the figure that the measured behaviour is almost always covered by the set of possible values predicted by QFSIM. The which simulation fails in the interval 380 - 410 minutes indicates that the coefficients should be better tuned in such operating region. This is not of great concern since the system is not supposed to operate in this region ("BTP"

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smaller than 65%). Such undesirable behaviour occurred because of an operator mistake. What is interesting is that the QFSIM simulation predicted that the "BTP" would penetrate the region below 65% at time 370 minutes. The QFSIM simulator would have thus advised the operator on line about such possibility.

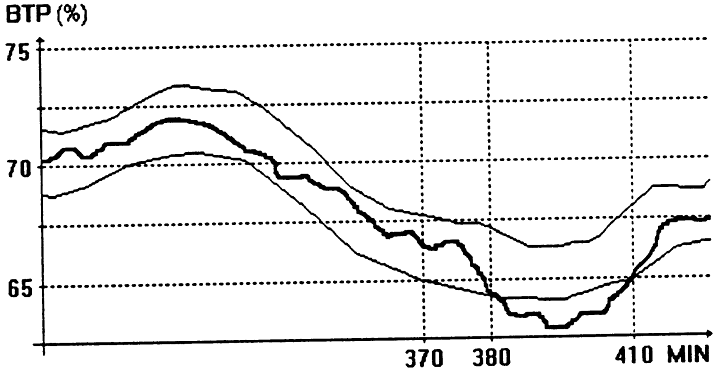


Fig. 5.2 - QFSIM predicted behaviour and measured behaviour of the "BTP".

The set of simulations performed by QFSIM with the acquired operation model is considered to be successful. Further work is being done in order to run the system on-line as an operator adviser. The coefficients were tuned considering the last 6 months operation. Since the quality of the raw material can significantly change coefficient values, extra work is to be performed in order to increase the reliability of the simulations.

## 6. DISCUSSIONS AND CONCLUDING REMARKS

Our claim in this paper is that qualitative methods based on interval (or fuzzy) arithmetic are adequate for modeling complex continuous processes. We showed that, although it is almost always impossible to define numerical models for complex processes, it is usually possible to define boundaries (intervals) for the system parameters. Indeed, some precision in terms of numerical values is always required. Most processes are controlled to work within operating ranges that tend to become narrower as requirements are increased or more knowledge is available. Optimum operation is directly linked to numbers in the monitoring of continuous processes.

Besides, for the effective use of interval (or fuzzy) based methods, soundness and completeness properties are of great importance. On the one hand, an incomplete method may fail in predicting important behaviours, and, on the other hand, a method that produces too much spurious behaviours, opening too much the range of possibilities for a variable value or a time interval is useless. Most qualitative interval or fuzzy methods like Fu-Sim [6], Q3 [1] and QFSIM Extremities Method are complete but not sound. QFSIM Discretization Method is sound but not complete. It converges towards completeness but is combinatorial. Special care has to be taken regarding such properties. We believe that further research is necessary in order to characterize which methods fit particular applications (depending on its dynamics, required accuracy etc) and to create more fulfilled methods regarding the properties mentioned and the computational complexity.

We have also presented the successful application of QFSIM, a particular fuzzy-based qualitative method, to model a complex siderurgical process at CST "Companhia Siderurgica de Tubarao", a Brazilian-Japanese company located in Vitoria-Brazil within the MMC Project [14]. Further work is being done in order to run the system on-line as an operator adviser.

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