Fuzzy Logic Control Applied to in-Vessel Composting

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Process control is of extreme importance in composting, because the biological process is influenced by various factors, such as temperature, moisture and oxygen. In addition, the material to be composted has typically a variable composition, which makes even more difficult to maintain the process parameters within the desired range. In-vessel composting has shown its superior performance in controlling not only the biological process but also the emission of odors and wastewater. Most industrialised in-vessel composters use PLC automation and sophisticated PC visualisation graphics. However, as in most computer applications, the software makes the difference and can add value to a composting system.

Bio-tunnel composting is an in-vessel system suitable to medium to large composting facilities, which is usually run by a PLC, while a PC provide the human interface. Various vendors have developed bio-tunnel systems in Europe, where recently the bio-tunnels have become the dominant composting technology. Ecomaster has successfully applied a Fuzzy Logic-based algorithm to the process control of its proprietary bio-tunnel composters. This approach allows for the codification of the operators' experience, by means of a set of rules that can assume any value between zero (false) and one (true). The evaluation and aggregation of the rules permits to compute the most suitable control action, i.e. a variation of the airflow delivered to the bio-mass. The proposed controller can be adapted to different operating conditions thanks to the extensive parameterization of the rules.

A measurable performance factor of the Fuzzy Logic is the start-up time of the Ecomaster systems, which is now one fourth of the previous time. Process stability and uniformity of the compost products are other parameters that have significantly improved.

Composting is a generic description of the biological process that is used for different applications, such as pathogen control, stabilisation of organic waste and bio-drying of RdF. These have often-conflicting goals: for instance bio-drying doesn't favour stabilisation, because when the moisture content goes below a determined level, the biological process is negatively affected. Also under these circumstances, the Fuzzy Logic control has proved to perform better than the traditional one.

Introduction

In-vessel composting is a definition often used with reference to any process that is not carried out outdoors. This wide category of enclosed systems includes more or less sophisticated composting technologies, which are enclosed by a building or a reactor. In some densely populated European countries, such as Italy, the attention given to the control of the composting odors is very high and this is why the bio-tunnel enclosed system, such as the system produced by Ecomaster, has become the preferred composting technology.

The composting process allows converting the organic fraction of different kind of waste into stable, humus-like materials that can be used in agriculture or for soil-remediation. It is based on the biodegradation of organic materials contained in the original substrate via the metabolic action of different families of aerobic bacteria, fungi, and actinomycetes (Huang *et al.*, 2000). The composting process may be divided into two main parts: a first part where organic materials are quickly biodegraded, called *High-Rate Phase* or *Active Composting Phase*, which last some

FIGURE 1. A bio-tunnel facility

weeks; then follows a second slower part called *Curing Phase*, that may last some months and allows to increase the content of humus-like materials in the final product. Inside the bio-tunnels operated by Ecomaster only the first part is carried on, as it is the one that can take the greatest profit while operated under an automatic control system.

A bio-tunnel plant is a modular system based on a number of processing units, each consisting substantially of a large concrete reactor having a width up to 30 feet and a length up to 100 feet. The reactors are provided with airtight front doors and an aerated floor that distributes the process air along the entire area of the tunnel. The batch process consists in filling the tunnels with a wheeled loader and empting them after the biological treatment which, depending on the application, lasts from seven to fourteen days.

In the Ecomaster system, each bio-tunnel has a blower connected to the floor air channels. The air drawn by the blower is a mixture of exhaust air coming from the same tunnel and fresh air taken from the material handling building located at the front of the bio-tunnel bank. Each bio-tunnel is maintained under a slightly negative pressure by means of a PID controlled suction system connected to a centralized blower. The exhaust air from all the tunnels is sent to a large bio-filter in order to control odor emissions. Typically, for each tunnel there are three air dampers, electrically driven, which regulate the flow of recirculated air, fresh air intake and process exhaust air going to the bio-filter. The bio-tunnel is mechanically simple, with no internal moving parts, but the process is automated by means of a PLC and a data acquisition and visualization PC. Various sensors are used to measure air temperature, compost temperature, air pressure and oxygen content. The control system, depending on the set-points of the process parameters, adjusts the air dampers and the speed of the blowers, which are provided with a variable frequency drive (inverter).

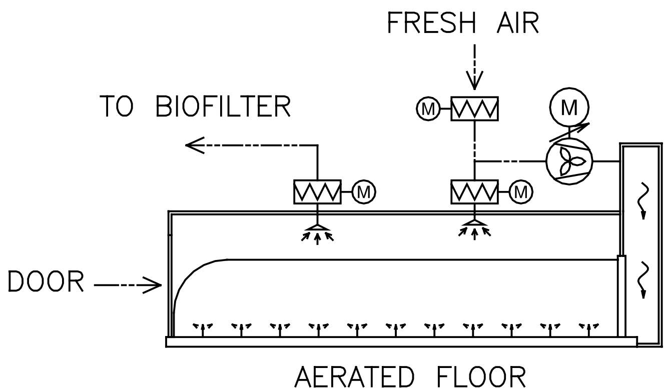

FIGURE 2. Scheme of a single bio-tunnel

Such a level of automation may appear excessive for a natural process such as composting, however it is a matter of fact that various pre-existing composting systems were shut down because of odor and process problems and later have been rebuilt using the bio-tunnel technology. All such facilities are now operating successfully.

The Ecomaster bio-tunnels usefulness is not limited to the control of the process odors: thanks to its flexibility the same system can be used for stabilisation, pathogen control and drying. The applications range from the production of quality compost from bio-waste to the bio-drying of RDF or the stabilisation of organic material screened from mixed MSW.

Such flexibility, anyway, comes at the cost of complexity in modelling the process, thus making the application of conventional control schemes unprofitable. For this reason, Ecomaster devised a Fuzzy Logic controller that avoids the need for a mathematical model of the system, requiring only a qualitative and empirical understanding of the process behaviour.

In the following section we will introduce some problems related to the control of the in-vessel composting process. Then we will describe the approach based on Fuzzy Logic that was used by Ecomaster and we will briefly discuss some results from a successful plant operated by a Fuzzy Logic controller.

Control Problem Formulation

Most modern control schemes require an exact or approximated knowledge of the mathematical model of the process being controlled. While adaptive control schemes exist than can deal with uncertainties in the model via some learning scheme (Ioannou and Sun, 1996; Farrel and Polycarpou, 2006), the composting process is a highly complex and uncertain process (Lin, 2006). Even if physical or empirical models were developed (Hogan *et al.*, 1989; Huang *et al.* 2000; Lin, 2006), a practical problem lies in the fact that the process depends on many parameters, like initial substrate composition, biomass and moisture content, that are difficult to measure or estimate in an industrial plant processing organic waste or WWT sludge (biosolids) coming from various sources. And, of course, a good model is useless or even detrimental if it is not possible to identify its parameters or to measure all its input variables during plant operation.

For this reasons a Fuzzy Logic Control System was devised, in order to take advantage of existing empirical knowledge of plant operators, requiring only the measurement of temperature of the composting pile and oxygen concentration in the air inside the bio-tunnel during the composting process. Fuzzy Logic inference systems allow to implement in a formal way qualitative reasoning typical of the human way of thinking (Zadeh, 1965) and were soon applied to control problems (Zadeh, 1972; Mamdani, 1974). Fuzzy Logic-based control and supervision systems found many applications in the field of waste treatment plants (Boscolo *et al.*, 1993; Carrasco *et al.*, 2004; Chen *et al.*, 2003; Estaben *et al.*, 1997; Lin *et al.* 2006).

Our approach to the control of the composting process is based on a qualitative model, whose inputs, outputs and influencing are highlighted in the following figure:

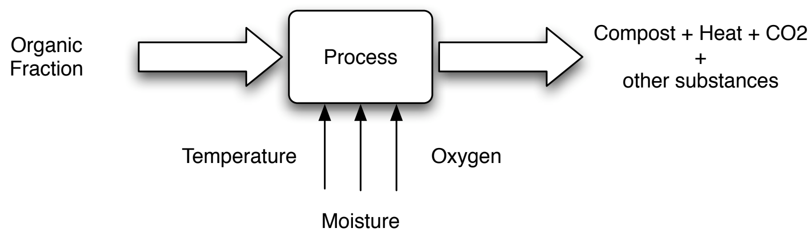

FIGURE 3. Scheme of the composting process

In the composting process, micro organisms consume the organic fraction and oxygen in order to produce stable by-products, CO_2, heat and other substances. O_2 concentration, temperature and moisture content are parameters influencing the microbial activity, and could also be all measured on-line, though in the proposed control scheme moisture content is not measured.

Temperature is one of the most important parameters that should be regulated in order to maximize microbial activity (MacGregor *et al.*, 1981), as temperature influences the growth of different populations of micro organisms (Strom, 1985; Ryckeboer *et al.*, 2003) that compete for the available nutrients in the composting substrate during meshophilic and thermophilic stages. The heat produced during the biodegradation is responsible for the natural temperature raise of the composting pile, which is characterised by a low thermal conduction. If not controlled, the temperature will increase until reaching values as high as 70-80°C, until a self-limiting mechanism will inhibit further heating, as microbial activity is reduced in this extreme thermophilic regime (MacGregor *et al.*, 1981). O_2 and moisture concentration also affects the biodegradation process, as O_2 is a necessary reagent in the aerobic biodegradation process, while water allows nutrients to be dissolved and made available to microbes (Li, 2006).

So, an ideal control system should regulate temperature, O_2 and moisture concentration to values that maximize microbial activity, in order to minimize the time needed for the completion of the composting active phase. As in the present implementation of the bio-tunnel moisture sensors are not included, only a simple feed-forward control of the moisture level is implemented by spraying a fixed amount of water (or waste water derived from the process) on the composting material at pre-determined times during the process. Instead, O_2 concentration and temperature are continuously monitored and regulated in order to achieve the following two objectives, where t represents the time:

1. regulate the O_2 concentration $c_{O_2}(t)$ above a minimum level $\bar{c}_{O_2}(t)$;
2. let the temperature $T(t)$ of the pile follow a suitable reference temperature time profile $\bar{T}(t)$.

The reference temperature time profile $\bar{T}(t)$ is set according to our past experience and to recommendations found in the literature. It can be divided into three main parts:

a. *warm-up*, during which the temperature is increased up to at least 60 °C;
b. *hygienisation*, that in order to abide to current Italian legislation requires a temperature above 55 °C to be held for at least three consecutive days;
c. *stabilisation*, during which the temperature is kept between 50 and 55 °C until a stabilised compost is obtained, ready for maturation.

In order to attain the two previously stated objective it is possible to control the blower regime and the mixture ratio between re-circulated and fresh air. As the internal pressure of the bio-tunnel is kept constantly under the outside level in order to avoid odor emission, any introduction of fresh air corresponds to the extraction of some air from the bio-tunnel. As the fresh air is usually colder, drier and more oxygenated than the air inside the tunnel, introducing it inside leads to the following effects:

1. the O_2 concentration inside the tunnel is increased;
2. the colder and drier air introduced inside the tunnel cools the composting pile via conduction and evaporation of pile moisture;

3. moisture and heat content inside the tunnel is reduced via extraction of air from the tunnel.

Recalling our qualitative description of the composting process and considering the flow of fresh air $q_A(t)$ directed inside the tunnel as the only input controllable in closed loop, the bio-tunnel is an inherently coupled SIMO system, as we cannot affect the O_2 concentration without affecting the temperature. Furthermore, this kind of coupling is dependent on the actual O_2 concentration and on the difference between the fresh air temperature and the pile temperature. For example, when the O_2 concentration is already high and there is a great temperature difference between the pile and the fresh air, the effect of fresh air introduction will be mainly a reduction in pile temperature. On the opposite side when the temperature differential and the O_2 concentration are both low, introducing fresh air will probably contribute to raise the temperature as the increase in microbial activity due to higher O_2 concentration will easily overcome the small heat loss due to conduction and evaporation.

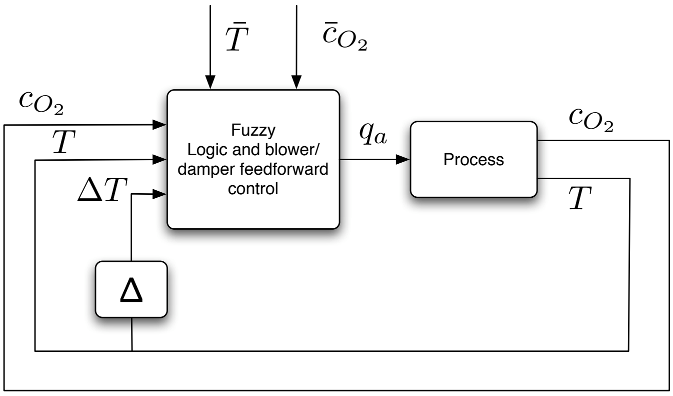

FIGURE 4. Scheme of Fuzzy Logic control

In the following section we will outline a Fuzzy Logic control system that, by measuring $c_{O_2}(t)$ and $T(t)$, will regulate them by acting on $q_A(t)$. This control system will embody readily available information from the qualitative model of the composting process and the experience of plant operators, without requiring an analytical model as conventional control schemes.

A Fuzzy Logic Control System

The proposed control scheme is implemented in discrete-time, with sampling time τ, and is depicted in FIGURE 4. The Fuzzy Logic block accepts the actual sampled value of the O_2 concentration $c_{O_2}(k\tau)$, the temperature $T(k\tau)$ and the temperature increase ratio $\Delta T(k\tau) := (T(k\tau) - T((k-1)\tau))/\tau$, so that it can be regarded as a particular kind of multivariable PD controller. The output of the block is the desired increase in the fresh air flow directed in the tunnel, so that the actual desired flow is computed as

$$q_A(k\tau) = q_A((k-1)\tau) + f(c_{O_2}(k\tau), T(k\tau), \Delta T(k\tau)), \qquad (1)$$

where f is the output of the Fuzzy Logic block. The quantity $q_A(t)$ is then converted to an actual blower regime and fresh air shutter position by means of a simple feed-forward controller.

The Fuzzy Logic block output is constructed by connecting the four standard blocks depicted in the following picture:

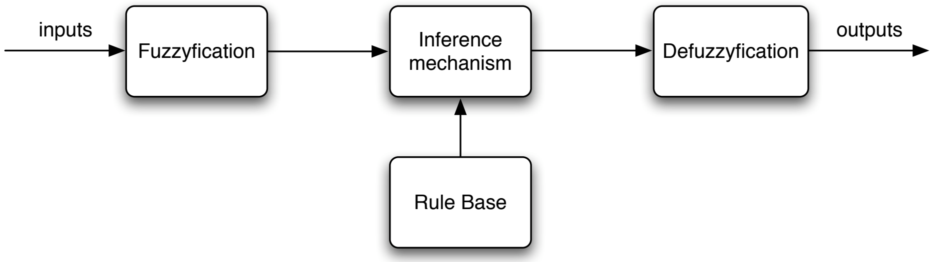

FIGURE 5. Scheme of a Fuzzy Logic Inference System

In the following section the operation of each block is briefly described: further details may be found in (Zadeh, 1965; Mamdani, 1974).

Fuzzyfication

Fuzzy Logic (FL) differs from ordinary binary logic as allowed logic values are not only 0 (false) and 1 (true), but may be any value in [0,1]. For this reason also standard logic operators must be redefined, according to TABLE 1. The numerical values of the n *crisp* inputs $u_i \in U_i \subset \Re$ to the FL are converted to several *fuzzy* values $u^*_{(i,j)} = \mu^{IN}_{(i,j)}(u_i)$, where $i = 1 \ldots n$, $j = 1 \ldots m_i$ and m_i is the number of *membership functions* $\mu^{IN}_{(i,j)}(u_i) : \Re \rightarrow [0,1]$ associated to the i-th input.

TABLE 1

Definition of Fuzzy Logic operators[1]

Operator	Definition
NOT a	1-a
a OR b	max(a,b)
a AND b	min(a,b) a*b
IF a THEN b	min(a,b)

[1]We will use the first definition of AND

Each fuzzy value $u^*_{(i,j)}$ represents to what degree the crisp input belongs to some fuzzy set described by the membership function. For example, in the present case the input $c_{O_2}(k\tau)$ may be associated to two fuzzy sets representing whether the O_2 concentration is "low" or is "high". In the control scheme implemented in the bio-tunnel systems, all the membership functions are trapezoidal.

Rule base

The brain of the FL control system is the *rule base*, which codifies the qualitative and empirical knowledge about how the plant should be operated. Every rule is a statement in the form "IF *premise* THEN *conclusion*", where the *premise* and the *conclusion* are statements requiring the inputs and outputs to belong to some fuzzy sets or combinations of them. For example, in a hypothetical FL velocity control system of a car, a rule may be "IF (the speed is *high* AND the time is not *late)* THEN throttle is *decreasing*". This means that the premise requires the input "speed" to belong to the fuzzy set "high" and the input "time" not to belong to the set "late"; if these requirements are fulfilled the rules say that the output "throttle" must belong to the set "decreasing". As usually more than a rule draws conclusions about the same output variable, the rules may be given a weight $w_r \in [0,1]$, $r = 1 \ldots n_{rules}$, in order to assign a priority to them. In the following section it will be explained how rules are computed and *aggregated*.

Inference mechanism

The inference mechanism actually permits to evaluate all the n_{rules} rules, draw a fuzzy conclusion about the desired output for each rule and then *aggregate* the results from rules influencing the same output. The premise fuzzy value $p_r(u)$ of the *r*-th rule is computed simply by applying the correct fuzzy logical operator to the values obtained by input membership functions. For example, the premise "the speed is *high* AND the time is not *late*" is computed as $\min(\mu_{high}(speed), \mu_{late}(time))$. The conclusion $c_r(y)$ of the *r*-th rule is computed as a function of the possible output value[1] $y \in Y \subset \Re$, by applying the fuzzy implication to the premise and to the output membership function of the fuzzy set appearing in the conclusion statement. For example the conclusion of the rule "IF (the speed is *high* AND the time is not *late)* THEN throttle is *decreasing*" is computed as. As the FL controller described here uses Mamdani type of rules, it should be noted that the conclusion is not a single value, but a function with values in [0,1]. This function represents how much each possible value of the control action *y* is likely to be taken.

In the non-trivial case, where more than a rule affects the output *y*, the conclusions from all the rules are aggregated by weighting them and taking the fuzzy OR of their values[2]. That is the aggregate conclusion is defined as $c^*(y) = \max_{r=1 \ldots n_{rules}} (w_r \cdot c_r(y))$. This is still a function of all the possible control action and takes a fuzzy value: in order to convert it to a crisp control action the value $c^*(y)$ should be *defuzzified*.

Defuzzyfication

The last step is the defuzzyfication. It consists in computing the value of *y* that best represents the function $c^*(y)$. A common algorithm is the so-called Center-Of-Area or Center-Of-Gravity, that is used in the bio-tunnel FL control system. The control action is computed as the *y* coordinate of the barycentre of the area comprised between the graph of $c^*(y)$ and the line *y*=0:

$$f(c_{O_2}(k\tau), T(k\tau), \Delta T(k\tau)) = \frac{\int_{y \in Y} y \cdot c^*(y) \mathrm{d}y}{\int_{y \in Y} c^*(y) \mathrm{d}y}. \tag{2}$$

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[1] For the sake of simplicity here we will limit our analysis to a single-output FL controller, as this is the case for the bio-tunnel control system

[2] Another approach for the aggregation consists in summing the conclusions $c_r(y)$ and limiting the sum by 1: $c^*(y) = \min\left(1, \sum_r c_r(y)\right)$

Results and Discussions

The Mamdani type FL controller described in the previous section was used for the control of Ecomaster plants that compost fine organics from MSW screening since late 2004, when it was installed in the newly built Sant'Agata facility, near Bologna, Italy. The controller uses a compact number of static rules devised thanks to the company past experience in controlling the composting process. It is implemented along with the remaining part of the plant control software on a Siemens S7 PLC, while an ordinary Windows PC is required for running our SCADA application. Furthermore, by using an internet connection, Ecomaster engineers can carry on remotely operated assistance session.

The SCADA application allows the plant operator to gather all the needed information about the process and to set reference values for temperatures, O_2 concentration, watering policies and process phases duration. All this information is presented in a simple and self-explaining manner, so that operators do not need any special training, nor any knowledge about FL. Anyway, Ecomaster engineers can set advanced parameters such as rules weights or membership function position in the input space. Furthermore it is possible to fully inspect historical data in order to gain insight into the performances attainable with different combinations of process set-points and controller parameters.

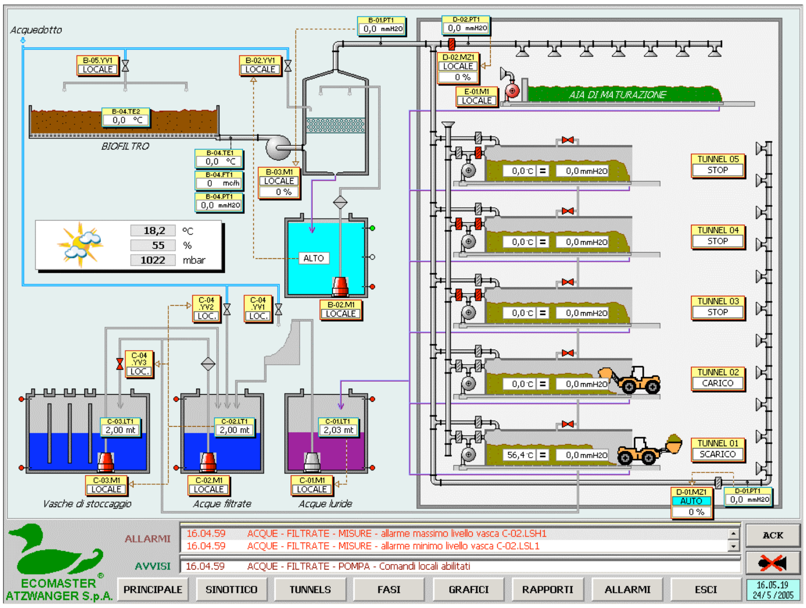

FIGURE 6. Screenshot of SCADA software

In the following graph it is possible to see the actual temperature time profile during some process runs at the Guanzate facility, near Como, Italy:

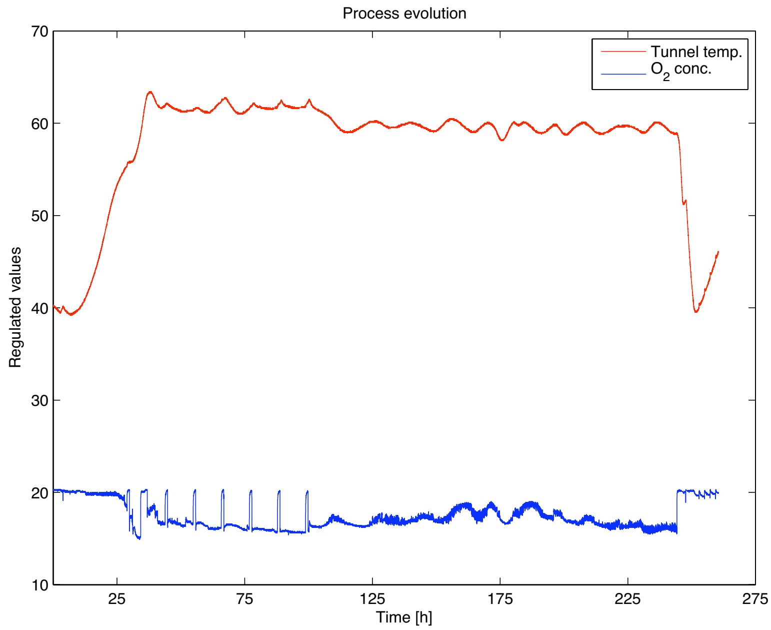

FIGURE 7. A composting process showing no oscillations

For that process run the temperature set points during the stabilisation phase were set just below 60 °C, as it can be seen after the 120[th] hour. We can see that O_2 concentration is always above the minimum of 14%.

In the following graph is it possible to see an oscillating behaviour due to a different setting of the FL controller parameters:

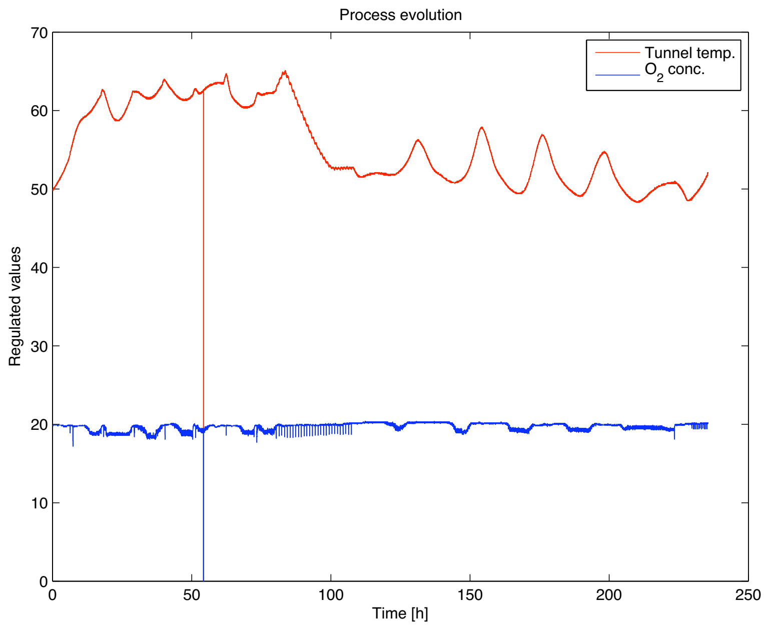

FIGURE 8. A composting process showing no oscillations

Anyway, a part from the oscillating behaviour, the controller was able to satisfy the requirements about the minimum and maximum temperature during the various process phases, that is: 60 °C in order to finish the warm up phase, at least 55 °C during the hygienisation phase and between 50 and 55 °C during stabilisation.

In the future, a useful feature to be introduced in the control system may be the adaptive tuning of all the FL controller parameters. In fact, though the controller proved to be robust with respect to variations in the initial composition of the pile and of other environment condition, nevertheless no sort of optimality is guaranteed. To this end it would be interesting to apply some adaptive technique from (Wang, 1993; Wang, 1994; Spooner and Passino, 1996; Spooner *et al.*, 2002).

In conclusion, the Fuzzy Logic control applied to the Ecomaster bio-tunnel technology has proven to be successful in efficiently controlling the composting process. Before the introduction of the FL, the time spent by Ecomaster's engineers for the system start-up was four times longer and the service calls frequent. We believe that the combination of a mechanically simple and sound system with the advanced FL control system is the key to the success established by the Ecomaster bio-tunnel technology.

Acknowledgements

The authors acknowledge the help given by eng. Manuele Lesa, who provided the process data that was presented in this paper.

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