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Modelling hybrid production systems through the ACD specification: a case study in the fibre-glass industry

Abstract

This paper is aimed at formalizing a model for hybrid production systems where the interactions between the continuous process parts and the manufacturing sub-systems are given by minor stoppages. The proposal is to represent the effects of the continuous process dynamics on discrete manufacturing sub-systems using Autoregressive Conditional Duration (ACD) models originally conceived to treat high-frequency and irregularly spaced financial transaction data. The proposed methodology has been tested on a real-life fibre-glass production plant exploiting simulation techniques. The physical model of the furnace and spooling-bushing department has been run in two different conditions: (i) the fibre-glass breakings, i.e. minor stoppages, on the spooling-bushing machines are generated according to the proposed approach; (ii) historical fibre-glass breakings data are used. The comparison between the simulation results shows that for three spooling-bushing machines only out of 24, the daily throughput of completed spools and the empirical distributions for the uncompleted spools weight are dissimilar under the two different conditions. Therefore, the ACD-based model proved useful for representing the occurrence of fibre-glass breakings on the spooling-bushing machines and, in more general terms, for the logical modelling of the hybrid production systems, where the relationships between continuous and discrete parts are given by minor stoppages.

1. Introduction

In the last years, hybrid systems have drawn the attention of mathematicians, engineers and control theory experts who developed theoretical frameworks, modelling approaches and analysis methods as different as their backgrounds are.

1.1. Hybrid systems

A broadly recognized definition of hybrid systems is still lacking. Many authors consider a hybrid system as a system consisting of (at least) two interacting sub-systems, characterized by continuous and discrete event dynamics respectively (Pettersson and Lennartson 1995, Demongodin and Koussoulas 1996, Stiver *et al.* 1996, Wieting 1996, Labinaz *et al.* 1997, Mostermann *et al.* 1998). A typical example of such systems is the household heating and cooling system (Niccolin *et al.* 1992): the heater and the air-conditioning sub-systems form a continuous system to be controlled; the thermostat is a simple 3-status (i.e. hot, cold and normal) discrete event system: home temperature is translated into one of the thermostat statuses and the thermostat's response is translated back to electrical currents to control the heater and the air-conditioning sub-systems. In this way the thermostat only perceives a symbolic version of the home temperature, and it generates a finite number of piecewise constant signals that turn (on or off) the heater or the air-conditioning sub-system.

Another definition of hybrid systems is provided by Branicky *et al.* (1998): a hybrid system can be modelled by equation (1):

$$\dot{x}(t) = \xi(t) \quad t \geq 0, \quad (1)$$

i.e. a differential equation that depends on the state vector (x), on the input vector (u) and on four kinds of discrete phenomena: (i) autonomous switching, the vector field $\xi(\cdot)$ changes discontinuously, or 'switches', when the state $x(\cdot)$ reaches some pre-defined boundaries. Formally, the system can be represented by two or more vector fields $\xi_i(\cdot)$ each of them defined in a given feasible region, for instance: $\dot{x}(t) = \xi_1(t)$ if $b(x) \leq 0$ $\dot{x}(t) = \xi_2(t)$ if $b(x) > 0$. If the system is currently described by $\xi_1(\cdot)$, when the state reaches the border of the feasible region for $\xi_1(\cdot)$, which means when $b(x) = 0$, the vector field switches to $\xi_2(\cdot)$; (ii) autonomous jumps, the continuous state $x(\cdot)$ changes impulsively on hitting particular regions of the state space; e.g.: $\dot{x}(t) = \xi(t) = -x(t) + \delta(x(t) - x_s)$, for $t \geq 0$, where the jump occurs when $x(\cdot)$ reaches x_s , according to the Dirac impulse; (iii) controlled switching, where $\xi(\cdot)$ switches in response to a control command, i.e. when $u(\cdot)$ (which contains also the input commands), reaches a given bound; a formal example is provided by the autonomous switching, when replacing $x(\cdot)$ with $u(\cdot)$; (iv) controlled jumps, where $x(\cdot)$ jumps in response to a control command; a formal example is provided by the autonomous jumps, when replacing $x(\cdot)$ with $u(\cdot)$.

Finally, according to Lunze (2002), hybrid systems are described by equation (2), (3) and (4):

$$\begin{cases} \dot{x} = f(x(t), u(t), t); & (2) \\ x(0) = x_0; & (3) \\ y(t) = g(x(t), u(t), t), & (4) \end{cases}$$

where x is the state vector, u is the input vector, y is the output vector, x_0 is the initial state and f and g are functions that do not satisfy the Lipschitz condition (Jeffreys and Jeffreys 1998). Figure 1 presents the state $x(\cdot)$ of one of the possible autonomous first-order systems; in this case the Lipschitz condition is not satisfied for $x = x_s$, i.e. $x(\cdot)$ includes state jumps, which occur every time the state reaches the threshold x_s .

The definition by Lunze (2002) is more restrictive than the one by Branicky *et al.* (1998): in the case of autonomous and controlled switching, the Lipschitz condition may be satisfied so that a switching system may not be considered as a hybrid system (according to Lunze), while switching systems are currently considered as an important subject of hybrid systems theory (Labinaz *et al.* 1997, Mostermann *et al.* 1998). This study will concern hybrid systems according to the first two definitions reported here.

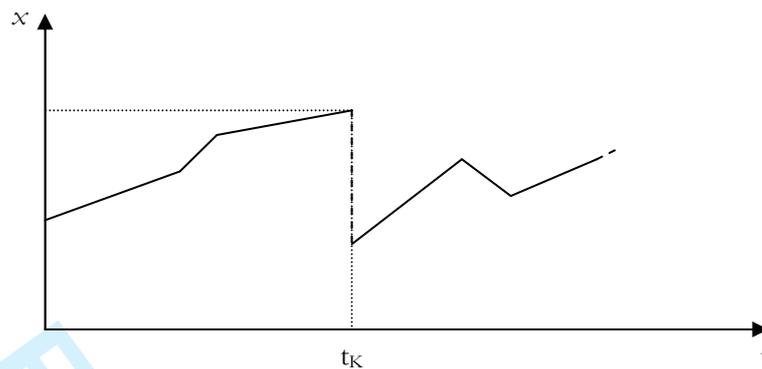


Figure 1 – Trajectory of an autonomous 1st-order hybrid system according to Lunze's (2002) definition

1.2. Aim and structure of the paper

Among hybrid systems it is possible to identify physical and non-physical hybrid systems (Labinaz *et al.* 1997). Physical hybrid systems are characterized by synchronous dynamics and the continuous variables are level variables (Wieting 1996), e.g. colliding bodies (Benveniste *et al.* 1993), tanks (Pettersson and Lennartson 1995, Stiver *et al.* 1996), electric circuits (Mostermann *et al.* 1998), etc. Non-physical hybrid systems are typified by discrete elements which introduce asynchronies (e.g. stochastic arrival times, queuing processes, etc.), and by continuous variables different from the level variables (Wieting 1996), e.g. highways, production plants, etc.

No specific modelling approach has already been developed for non-physical hybrid systems and, therefore, for hybrid production systems. In particular, when dealing with production environments, where the interactions between the continuous process parts and the manufacturing parts are given by minor stoppages, this lack of approach does not allow either sound simulation studies to be conducted (Law and Kelton 2000) or minor stoppages to be effectively faced (Cigolini and Rossi 2004). Such systems are quite popular in many branches of industry (e.g. plants for pulp and paper production, soaking pit furnaces, etc.) and minor stoppages, which are often overlooked (due to the short time length of each single stoppage), represent a large amount of working time: for instance Kuhmonen (1997) observed, for a 17-machine job shop, more than 27 000 minor stoppages per year, which corresponded to 9 500 production hours lost; Noè and Rossi (2003) counted, for a specific 12-machine department, more than 220 minor stoppages per day (on average), corresponding to a 12.5% loss of the available production capacity.

As a consequence, this paper is aimed at formalizing and testing a modelling approach for production systems where the interactions between the continuous process parts and the manufacturing sub-systems are given by minor stoppages.

Briefly, the proposed approach consists in representing the effects of the continuous process dynamics on discrete manufacturing sub-systems by means of Autoregressive Conditional Duration (ACD) models (Engle and Russell 1998), originally conceived to treat high-frequency and irregularly spaced financial transaction data.

The paper is arranged as follows: section 2 is devoted to presenting both the current hybrid systems modelling approaches and ACD models (in particular, the ACD specification is described and the Exponential ACD (EACD) model is introduced). Section 3 presents the new approach and introduces the analogy between minor stoppages and very liquid shares. In section 4 the proposed model is applied to a plant belonging to the fibre-glass reels industry; more in detail, the ACD-based simulation is compared to the simulation of the same system fed by minor stoppages historical data, thus allowing to prove the effectiveness of the proposed approach. Finally, section 5 presents some closing remarks and suggestions for future research paths.

2. Background

This study concerns two main areas: hybrid systems modelling, become a major research subject in the last decade, and ACD specification raised with Engle and Russell (1998) and thrived thanks to many authors (e.g. Zhang *et al.* 2001, Engle and Lunde 2003, etc.).

2.1. Hybrid systems modelling

Literature dealing with hybrid systems is characterized by various approaches from the viewpoint of the techniques used for the logical modelling, e.g. automata and transition systems, dynamical systems and hybrid Petri nets. The pioneering idea of modelling a hybrid system lies in representing it as an automaton (Alur *et al.* 1993), where the nodes are the continuous sub-systems corresponding to given values of the discrete variable that characterizes the hybrid system, and the arcs represent the (discrete) transitions which allow the (hybrid) system to pass from the current continuous sub-systems to the next one (see also figure 2). The transitions can represent both switching phenomena and jumps.

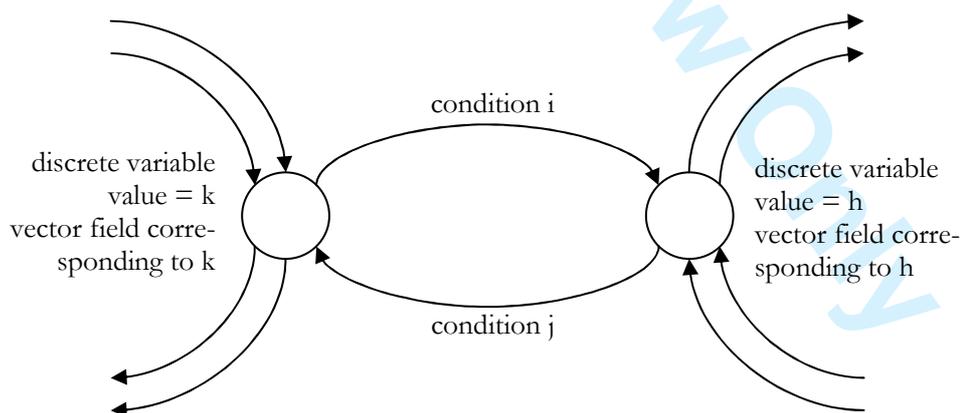


Figure 2 – Hybrid system represented as an automaton.

The modelling approaches of hybrid systems based on dynamical systems identify the feasible region within the state space. These approaches generate discontinuously changes of the vector field describing the state evolution (switching phenomenon) and/or abrupt changes of the values of the state variable (jumps) when

the same state variable hits the boundaries of the region or predetermined areas inside it (Branicky 1996). A graphical example of these modelling methods is given (for a three-dimension state space) in figure 3: when the state reaches one of the boundaries of the feasible region K a switching phenomenon or a jump occurs.

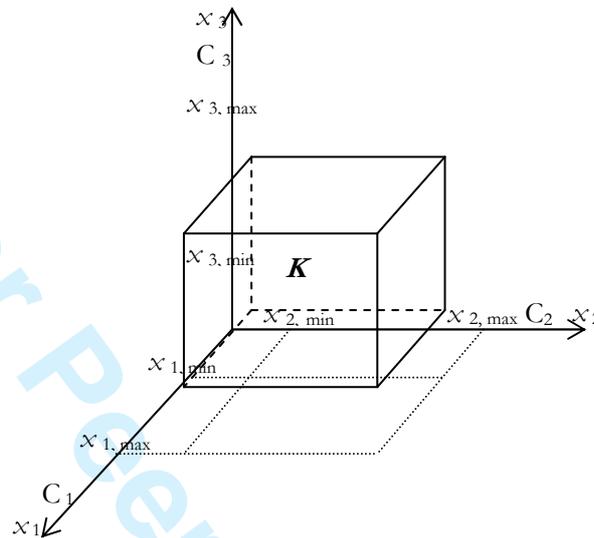


Figure 3 – Hybrid system as a dynamical system

Finally, modelling hybrid systems through hybrid Petri nets is similar to the automata-based approach. Continuous dynamics are represented by continuous sub-nets (i.e. the nodes of the automaton) made of continuous places and transitions, whereas the activation of the different continuous sub-nets are regulated by means of discrete sub-nets (i.e. the arcs of the automaton) composed of discrete places and transitions (Demongodine and Koussoulas 1996, Alla and David 1998, Champagnat *et al.* 1998). The main strength of this approach lies in that it combines the idea of the system as an automaton and the effective representation driven by the Petri nets formalism, which allows to depict a particular system's status, as well as to describe the system's complete evolution.

Table 1 presents a taxonomy of some hybrid systems modelling approaches. Each approach is classified according to the three schools of thought mentioned before, i.e. automata and transitions, dynamical systems and hybrid Petri net. The references, the current applications and the classes the applications belong to (i.e. physical or non-physical systems) are also reported. In particular, table 1 highlights that the logical modelling of non-physical hybrid systems (and, as a consequence, also of hybrid production environments) has been so far almost neglected, even considering the model by Wieting (1996) as applied to physical hybrid systems only, because of the great simplification made by the author to the analyzed soaking pit furnace.

School of thought	Reference	Current applications	Hybrid systems classes
Automata and transition systems	Alur <i>et al.</i> 1993	Systems composed of plant temperature, thermostat and heater	Physical
	Tittus and Egardt 1994	Systems composed of three tanks, one pump and two valves (and other tanks systems)	Physical
	Deshpande and Varaiya 1995	No practical applications (only theoretical applications on several equations systems)	
	Mostermann <i>et al.</i> 1998	Diode-inductor circuits (and other electrical circuits)	Physical
Dynamical systems	Asarin <i>et al.</i> 1995	No practical applications (only theoretical applications on several equations systems)	
	Stiver <i>et al.</i> 1996	Systems composed of a thermostat, a room and a heater Distillation column (Theoretical application on an equations system – the double integrator)	Physical
	Branicky <i>et al.</i> 1998	No practical applications (only theoretical applications on several equations systems)	
Hybrid Petri nets	Petterson and Lennartson 1995	Filling and emptying processes of a vessel Batches production system (Theoretical application on an equations systems)	Physical
	Wieting 1996	Very simplified soaking pit furnace	Non-physical (practically physical)

Table 1 – Taxonomy of hybrid systems modelling approaches

2.2. Autoregressive Conditional Duration (ACD) models

The most relevant application of ACD models is to measure and to forecast the intensity of transaction arrivals (i.e. the instantaneous quantity of transactions) on the stock market.

Stock market is characterized by the alternation of very frenetic periods and periods with few exchanges that reflects the asset liquidity variations: frenetic periods correspond to short durations, very volatile prices and high volumes. This feature discourages the application of standard econometric models, since data are to be aggregated in predetermined intervals, thus causing loss of information.

To this purpose, ACD models are well suitable to represent the dynamics of temporal intervals (durations) between subsequent transactions: arrival times are considered as stochastic variables which follow a point process and the unevenness of transactions over time can be taken into account (Engle 2000).

Moreover, the durations dynamics analysis (Engle and Russell 1998) points out that the transactions occurrence depends on the (past) history, since short and long

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durations are respectively followed by short and long durations: such phenomenon, according to Engle and Russell (1998) is also called ‘clustering’. For this reason, the basic formulation of the model, as shown below, parameterises the conditional intensity as a function of the time between past events.

Let $x_i = t_i - t_{i-1}$ be the random variable (called duration) that represents the interval between two subsequent arrival times. The ACD models are specified in terms of the durations density conditional on the previous values of x . Let ψ_i be the conditional expectation of the i^{th} duration and let $F_i = \{x_{i-1}, \dots, x_1\}$ be the process history until the time t_i . ψ_i is given by equation (5):

$$\psi_i = E(x_i | F_{i-1}; \theta) = \psi_i(x_{i-1}, \dots, x_1; \theta). \quad (5)$$

The i^{th} duration, instead, is given by equation (6):

$$x_i = \psi_i \varepsilon_i, \quad (6)$$

where $\{\varepsilon_i\}$ are independently and identically distributed with density $p(\varepsilon; \phi)$, where p is a distribution with expectation equal to 1 (because of the multiplying impact of the error on the durations), and θ and ϕ are variation free. Equation (5) and (6) and the conditions on ε_i , p , θ and ϕ are the general structure of an ACD model.

A very common functional shape of ψ_i is the linear one (see equation (7)), which expresses the conditional expectation of a m -memory process, i.e. a process where the next transaction depends only on the previous m 's:

$$\psi_i = \omega + \sum_{j=1}^m \alpha_j x_{i-j} \quad (\omega > 0). \quad (7)$$

A linear model without the limited memory feature can be specified by equation (8), which allows all the past durations to be included in the conditional intensity even considering a finite number of lags; equation (8) and (6) and the conditions on ε_i , p , θ and ϕ represent the linear specification of an ACD(m , q) model, where m and q refer to the order of the lags:

$$\psi_i = \omega + \sum_{j=1}^m \alpha_j x_{i-j} + \sum_{j=1}^q \beta_j \psi_{i-j}. \quad (8)$$

A noteworthy simple version of linear ACD models is the Exponential ACD (EACD) model, which considers the error to be exponentially distributed. The hazard function of an exponential random distribution is not time-dependent and it equals the value of the parameter. In this case, since the error expectation must be equal to 1, also the distribution parameter must be 1; then the baseline hazard is constant and equal to 1. As a consequence, also the durations conditional on the past history follow an exponential distribution with parameter (in the case of a single lag) $\psi_i = \omega + \alpha x_{i-1} + \beta \psi_{i-1}$. The main limit of EACDs lies in that they depend only on one parameter and the hazard is constant (Engle and Russel 1998, Zhang *et al.* 2001, Engle and Lunde 2003).

An example of how EACD models can be used is presented in the followings. A single-lag EACD model is introduced and the parameters are supposed to be

known; the parameters estimate methodology is explained in section 3. The single-lag EACD model is described by the recurrent equation (9) and (10):

$$\psi_i = \omega + \alpha x_{i-1} + \beta \psi_{i-1}, \quad (9)$$

$$x_i = \exp(\psi_i), \quad (10)$$

where ω , α and β are supposed to be equal to 287.708, 0.554 and 0.239 respectively.

Equation (10) means that the generic duration (x_i) is drawn from an exponential probability function with parameter given by the corresponding conditional expectation (ψ_i), according to the exemplifying case is shown in table 2.

i	$\psi_i (= 287.708 + 0.554 \cdot x_{i-1} + 0.239 \cdot \psi_{i-1})$ [seconds]	$x_i (= \exp(\psi_i))$ [seconds]
0		$\exp(1,406.49)=2,980.61$
1	$287.708 + 0.554 \cdot 2,980.61 + 0.239 \cdot 1,406.49=1,779.27$	$\exp(1,779.27)=1,083.78$
2	$287.708 + 0.554 \cdot 1,083.78 + 0.239 \cdot 1,779.27=1,532.45$	$\exp(1,532.45)=1,482.25$
3	$287.708 + 0.554 \cdot 1,482.25 + 0.239 \cdot 1,532.45=1,490.94$	$\exp(1,490.94)=456.928$
4	$287.708 + 0.554 \cdot 456.928 + 0.239 \cdot 1,490.94=1,222.90$	$\exp(1,222.90)=1449.47$

Table 2 – Duration estimate by means of an EACD model

In particular, table 2 presents the estimated inter-arrival times (in seconds) with reference to an arrival process which follows the EACD model represented by (9) and (10). The initial expectation value (ψ_0) is supposed to be equal to 1 406.49 seconds. The 1st column of table 2 contains the index of the conditional expectation and of the corresponding duration; the 2nd column reports the conditional expectation (calculated by means of equation (9)), while the 3rd column reports the duration, that is the inter-arrival time drawn from the exponential probability distribution (described by equation (10)).

3. The proposed approach

This section is aimed at identifying a methodology for modelling hybrid production systems where the interactions between the continuous and the discrete (i.e. process and manufacturing) parts are represented by minor stoppages (occurring on the discrete part) due to incorrect values of the continuous variables (characterizing the continuous part).

3.1. Modelling approach framework

Minor stoppages have been compared to very liquid shares in terms of duration, since even for minor stoppages the variable of interest is the time interval between a stoppage and the next one. Moreover, the frequency of both phenomena is very high: on a liquid share thousands of transactions per day can take place, whereas minor stoppages can be repeated many times per shift or even per hour (Kuhmonen 1997, Noè and Rossi 2003). Finally, the time intervals between both transactions and minor stoppages are typically very uneven, i.e. they cannot be grouped in few

ranges given by pre-defined values and they depend on the past history, i.e. they are typified by the clustering phenomenon. Minor stoppages clustering is mainly due to the fact that they are caused by an abnormal evolution of continuous variables, which do not immediately recover correct values and/or trends. For instance, with reference to a production context where minor stoppages depend on the temperature of a fluid mass, it is highly probable that several minor stoppages will occur within a very limited time fence since the temperature of the fluid mass cannot be immediately brought back over the pre-set value.

Table 3 summarizes the analogies above.

Variable of interest	Duration
Frequency	High/Very high
Intervals	Irregular
Series	Auto-correlated
Typifying phenomenon	Clustering

Table 3 – Analogies between minor stoppages and very liquid shares

Due to the effectiveness of ACD models in representing the transactions on (very liquid) shares, the proposal of this study lies in modelling the minor stoppages occurrence on the manufacturing sub-system through the ACD specification (Rossi 2004). Once the ACD model to be applied to a real-life production system is defined, the parameters involved in the distribution have to be assessed and, to avoid biased estimators for each parameter, the maximization of the log-likelihood function is recommended.

Figure 4, by means of the so-called attributed Petri nets formalism (Reisig and Rozenberg 1998), shows the way the proposed approach represents the occurrence of minor stoppages on the manufacturing part of a generic hybrid production system. The discrete transition T_a becomes active (i.e. starts to fire) when a token is in place P_a ¹ and calculates both the expected value ψ (see section 2) and the value of the stochastic variable x , i.e. the duration between the previous and the next minor stoppage, according to the formulas referring to the ACD model employed. Then, transition T_a assigns the values previously obtained to the corresponding attributes of the token that will be created in the discrete place P_b (the attributes are named after the variables, i.e. ψ and x respectively).

When a token is in place P_b , transition T_b becomes active and starts to fire: after a time given by the attribute x , transition T_b releases a token in the discrete place P_c assigning to the token's attributes the new values of the regressive variables required by transition T_a to calculate the new values of ψ and x (in figure 4 the token attributes are generally indicated by ω , α and β). Finally, transition T_c is activated: it allows the value W to be assigned to the state attribute of the token representing the condi-

¹ Given the initial mark depicted in figure 4, a token is always present in place P_a ; this place is connected to T_a by means of a test arc, which does not involve any passages of tokens through itself.

tion of the manufacturing part (in this case W corresponds to the state where the system is down due to minor stoppage). At the same time, the presence of a token in place P_c activates transition T_a , which cancels the token in place P_c and creates a token in place P_b after having calculated the new values of ψ and x and after having made the appropriate assignments.

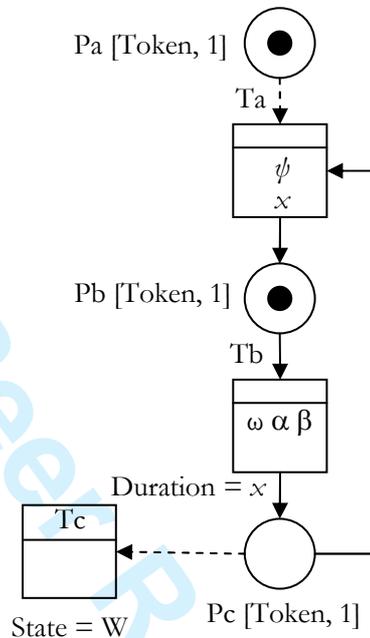


Figure 4 – Graphical representation of the proposed approach

3.2. Logical model definition

Figure 4 and the above description deal with the structure of the approach proposed for representing the minor stoppages occurrence with reference to hybrid production systems. As a matter of fact, to completely define a logical model deriving from the presented methodology, it is necessary to identify the ACD specification to be utilized and to estimate the parameters of the latter.

The ACD model can be chosen by analysing the physical behaviour of the real system to represent. Depending on the minor stoppages characteristics a model with a constant or a variable hazard can be preferred. As concerns the nature and the shape of the model instead, the single-variable and the linear ones are suggested respectively (as a matter of fact, the multi-variable models are not completely developed yet, and in most applications the problem of non positive conditional expectation, strictly connected to the use of linear shape, can be disregarded, see paragraph 2.2).

With reference to the parameters setting, it is necessary to choose how many memory steps the selected model must be provided with and to evaluate its parameters. This setting has to be carried out according to the scheme depicted in figure 2. In particular, inputs of the evaluation phase are: historical data, given by the durations between subsequent minor stoppages, and the equations representing the $m \cdot q$ ACD models which could be potentially used (given the selected single-variable and

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linear ACD specification, if m and q refer to the order of the lags, $m \cdot q$ are the possible combinations of memory steps, see figure 5). The applied evaluation method instead is the log-likelihood maximization one (Green 2000). It allows to identify the parameters evaluations, whereas the choice condition is to select the model with the lowest Schwarz criterion value (it is necessary to use the information criteria because, for models with lagged values, the higher the number of considered lags, the higher the maximum log-likelihood value).

4. Test

This section is devoted to testing the proposed approach by applying it to a production system belonging to the fibre-glass industry (see figure 6) and composed of furnace, distribution channels and spooling and bushing departments.

4.1. Production system configuration

The furnace, where the vitrifiable mixture is continuously introduced and the fusion process takes place, has two series of 16 burners, each of them composed of a tank containing warm air and a methane pipe. The air is introduced in the system by means of a huge fan placed under the furnace floor; then the air is heated by passing twice along the external layers of the chimney that expels the fusion fumes.

Once air and methane have been mixed, they are introduced in the furnace where, due to a temperature of more than 1300 °C, they catch fire concurring to heat the furnace roof. The heat radiated by the roof transforms the vitrifiable mixture into a fluid mass, whose temperature is determined by the radiation intensity and by the threefold action of: (i) two series of electrodes placed on the furnace floor; (ii) the convection motions inside the fluid mass; (iii) the gaseous and vitrifiable mixtures introduced in the furnace. Since the furnace cannot be switched off before the end of its life cycle time (i.e. about nine years), production is organized on 365 days per year basis.

The fused glass is transferred to the spooling department by means of a distribution system composed of one main and two secondary channels, where – due to the heat dispersion – temperature is reduced.

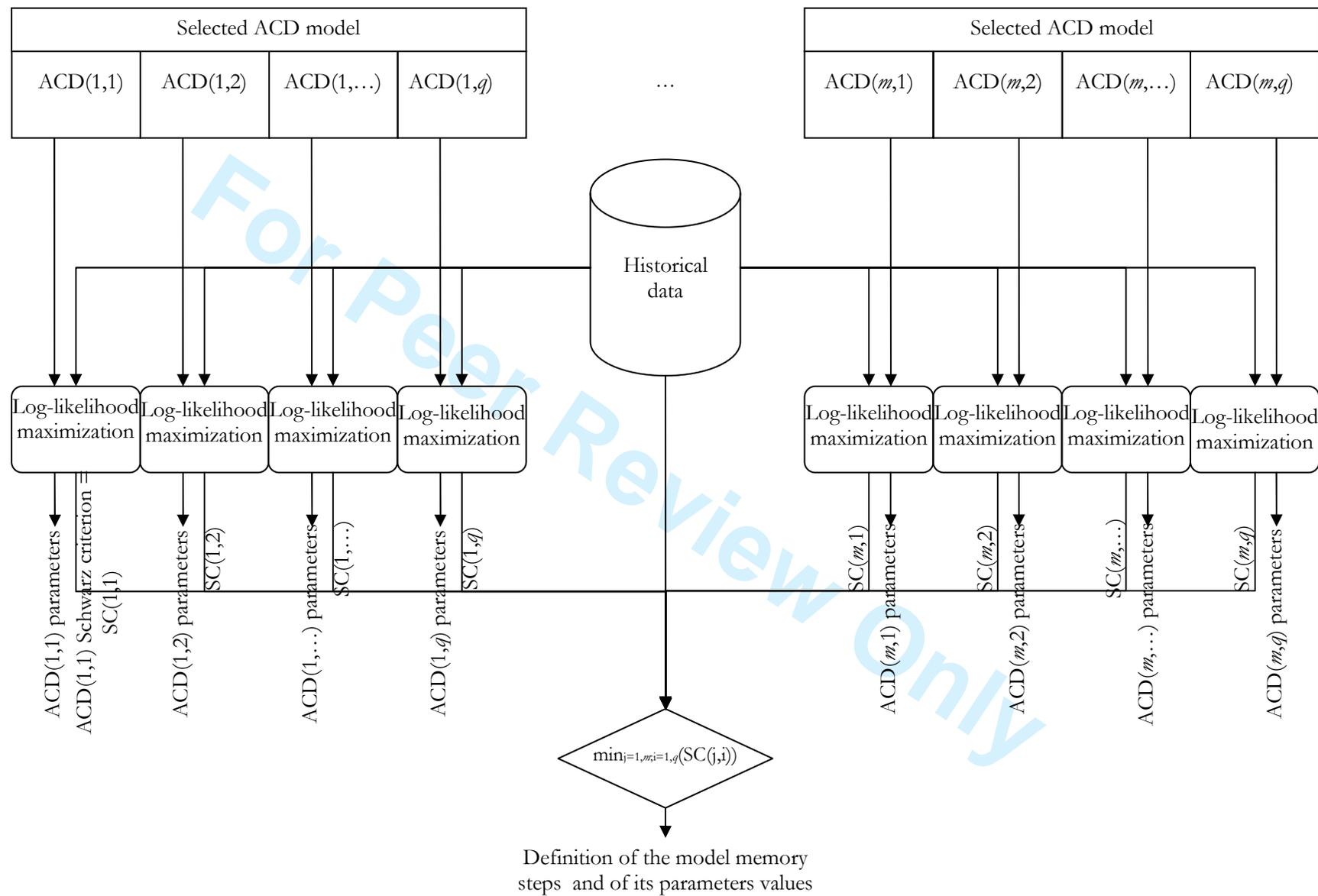


Figure 5 – Scheme of the estimate procedure

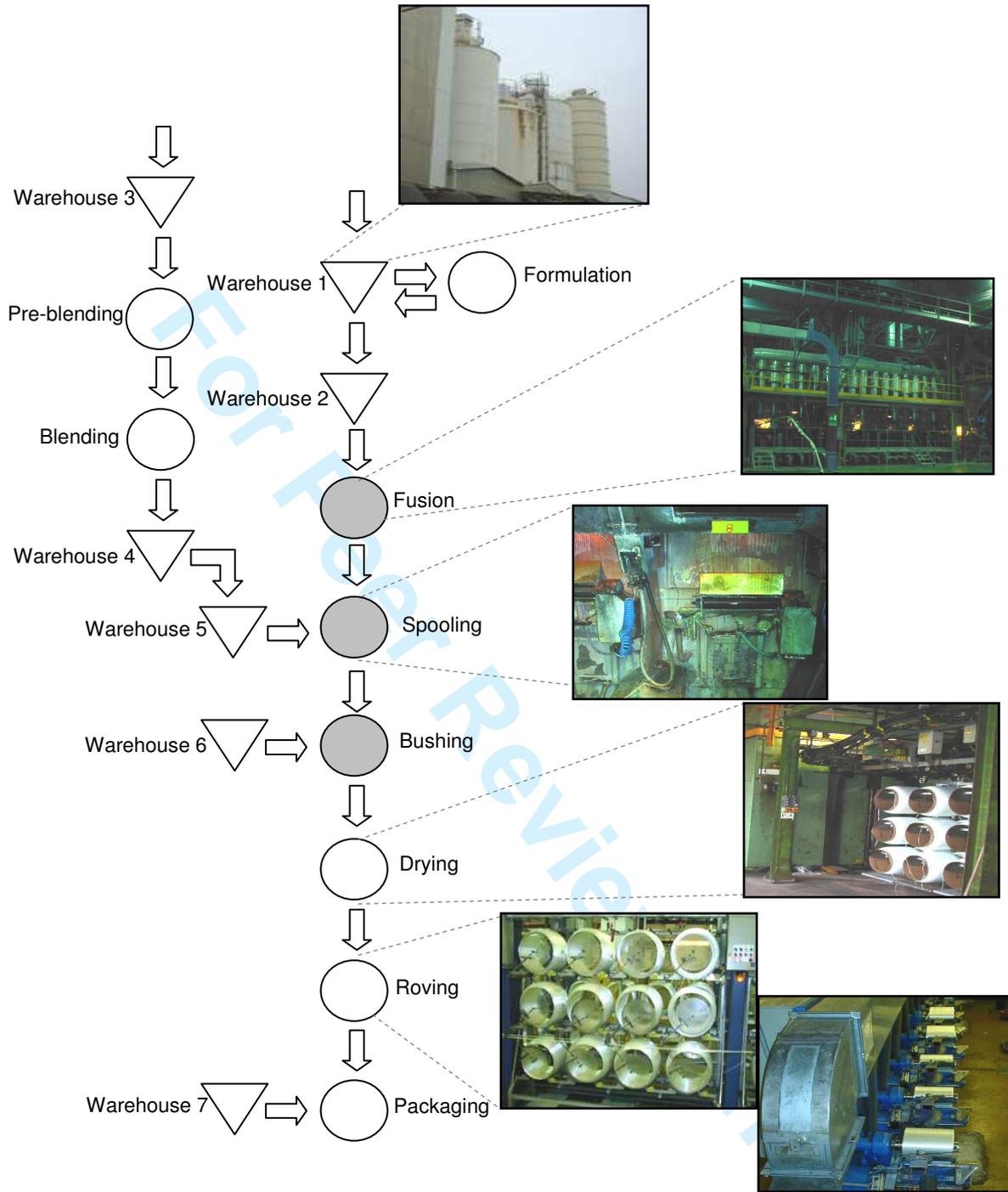


Figure 6 – Production flow of the whole manufacturing system; the shaded circles represent the considered hybrid system.

The channels have control and process thermocouples for checking and increasing the fluid mass temperature respectively. The spooling department under study is composed of 24 spooling machines (12 for each secondary channel), which transform into fibres the fused glass pouring in them. Spooling machines are specified by the theoretical production capacity (in terms of kilograms per day referred to the fluid mass processed). Each machine switches from the ‘in-operation’ status to the ‘not-in-operation’ status when a fibre-glass

breaking occurs. This minor stoppage, which represents the impact of furnace and distribution channels on the downstream departments, is due to either impurities on the fluid mass or wrong values of the pouring fused glass temperature: too high or too low temperatures correspond respectively to too fluid or too rigid fused glass; in both cases the spooling process can be uneven and the fibres can be broken. Since the pouring mass in the channels is a *continuum*, whenever the fused glass temperature is wrong for a spooling machine, the same occurs also to the adjacent machines. As a result breakings in adjacent machines often occur within a very limited time fence, while also isolated breakings due to the impurities on the fluid mass can occur.

The bushing department is similar to the spooling one, consisting of 24 machines (one for each spooling resource) that wind up the fibre-glass in coils around cardboard cores. Each bushing machine is equipped with a working and a stand-by position (see also figure 7); if the spooling machine is not in operation the corresponding bushing one cannot work and *vice versa*, while the bushing machine is forced to stop only when both its working and stand-by positions are occupied by finished coils. For this reason, when the spooling process is forced to stop due to a breaking, the coil in the corresponding bushing machine stops being processed, generally it does not reach the standard weight of 32 kg, and the fused glass continues to pour (thus producing wastes) until the spooling machine is re-started. The technical time required re-starting the spooling process ranges between three and five minutes and two operators are assigned to repair the fibre-glass breakings (one every 12 machines).

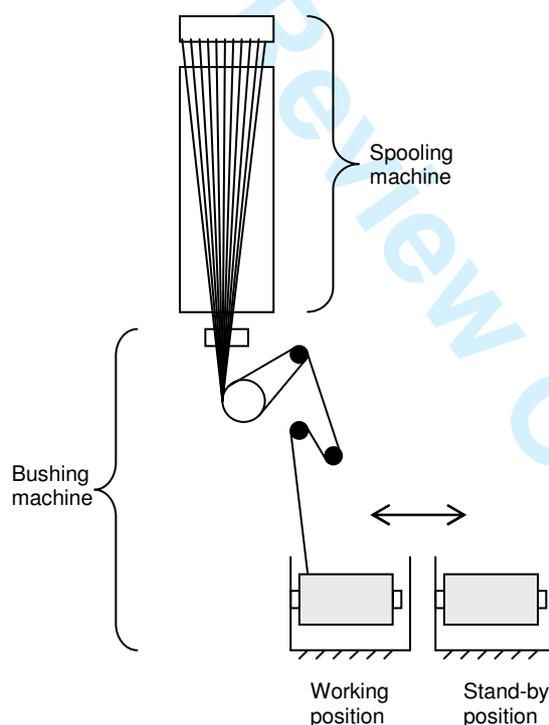


Figure 7 – Scheme of the spooling and bushing machines

As a consequence, the spooling and bushing departments (and each couple of spooling and bushing machines) can be considered as one department and one machine respectively and hereinafter referred to as 'spooling-bushing' department/machine. Moreover, two ro-

bots (one each series of 12 machines) are used to remove the finished coils from the stand-by positions and to bring them to a pre-assigned loading area: the distance between two adjacent bushing machines is four meters; the robots speed is equal to 0.2 m/s and the technical loading / unloading time is around 30 seconds. In the loading area, coils are loaded on six-slot metal cores, depending on the kind of glass they are made of. Once all the slots are occupied, the cores are transferred to the downstream production phases.

4.2. Hybrid system structure

The above described tandem furnace and spooling-bushing department can be considered as a hybrid system according to both definitions applied (see paragraph 2.1). Let us firstly consider the most formal one (see Branicky *et al.* 1998). The status of the production system under study is given by the pair (x, k) , where x represents the temperature of the fused glass coming out of the furnace (i.e. the continuous state of the system) and the Boolean $k(t)$ represents the discrete state of the downstream spooling-bushing machine (i.e. in-operation or not-in-operation). The system dynamics can be modelled by means of equation (1) and (11):

$$k(t) = \begin{cases} 1 & x_{\min} \leq x(t) \leq x_{\max} \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

Equation (1) and (11) depend on the state vector x , on the input vector u and on two discrete phenomena: (i) the activation (or the shutdown) of specific burners when the fused glass temperature reaches certain levels. This means that the vector field $\xi(\cdot)$ changes discontinuously (i.e. switches), when the state $x(\cdot)$ hits certain boundaries. In more formal terms, this means that the system can be represented by two (or more) vector fields $\xi_i(\cdot)$ each of them defined in a certain feasible region, i.e. the system is an autonomous switching, according to Branicky *et al.* (1998); (ii) the fibre glass breaking and the consequent transition in the spooling-bushing machine status (from in-operation to not-in-operation), when the fused glass temperature reaches certain levels. This means that the discrete state $k(\cdot)$ changes impulsively when the continuous state hits certain regions of the state space, which can be regarded as a particular type of autonomous jumps.

Even according to the less restrictive definition by Pettersson and Lennartson (1995), Demongodin and Koussoulas (1996), Stiver *et al.* (1996), Wieting (1996), Labinaz *et al.* (1997), Mostermann *et al.* (1998), the production sub-system described above can be considered as a hybrid system: the furnace is the continuous part characterized by continuous variables (i.e. the fused glass temperature), the downstream spooling-bushing department is the manufacturing part governed by discrete-event logics and the fibre-breakings represent the relation between them.

4.3. Application of the proposed approach

The experience of the fibre-glass industry practitioners suggests that the temperature dynamics of the fluid masses pouring in three adjacent spooling-bushing machines influence each other. So the fibre breakings occurring on a three-machine work-centre can be represented as a single stochastic process. This means that one ACD model represents the fibre breakings on a three-machine work centre made up from adjacent spooling-bushing ma-

chines. To define the model, it is necessary to select the ACD specifications to be used and to estimate the parameters.

Since the fibre-glass breakings do not depend on any kinds of wear² and, as a consequence, their occurrence probability does not increase over the time, an econometric model characterized by a constant hazard is sufficient to represent the breakings occurrence, and – as a consequence – the single-variable EACD model has been selected. Model parameters selection (i.e. how many memory steps the model is provided with) and their estimates have been carried out for each three-machine work-centre of adjacent spooling-bushing machines according to the scheme depicted in paragraph 3.2 and in figure 5. The input of this estimation phase are: (i) the historical data, given by the time records (in seconds) of all the events (i.e. fibre-glass breakings and spooling-bushing machine re-starts) occurred during a fortnight (a larger period is not taken into account due to the need to have two disjoined sets of historical data for the evaluation phase and for the real test phase respectively – see paragraph 4.4); (ii) the equations representing the 16 models which could be potentially used (i.e. from EACD(1,1) to EACD(4,4)).

The output of the estimation phase is presented in table 4: it depicts, with reference to each triple of adjacent spooling-bushing machines, the estimated values of the parameters ω , α_j and β_j , required to calculate the conditional intensity ψ_i according to the linear ACD specification (see equation (7)) and the minor stoppages durations conditional on the past history, according to the EACD model (see section 2. Both conditional intensity and duration are given in seconds).

Machine	ω	α_1	α_2	α_3	α_4	β_1	β_2	β_3	β_4
101-103	287.708	0.2390				0.5540			
104-106	295.401	0.1230	-0.013	0.0380	0.124	0.7520	-0.039	-0.9500	0.74
107-109	1,830.088	0.1490	0.131			-0.9050			
110-112	13.673	0.0710	-0.084	0.0680		2.3810	-2.339	0.8965	
201-203	5,210.915	0.0860				0.4660	-0.796		
204-206	1,297.689	0.1970				-0.0825			
207-209	191.074	0.0490	0.036	0.0215		-0.1310	0.914		
210-212	634.686	0.1605	-0.112	0.0320	0.085	1.2320	-0.997	0.2080	

Table 4 – Results of the estimation phase

Table 4 shows that the persistence of the past fibre-breaking occurrences is higher for the spooling-bushing machines that are more distant from the main distribution channel (actually, the number of lags to be considered in the corresponding EACD model increases with the spooling-bushing machines indexes). This fact is coherent with the temperature dynamics of the fluid glass experienced by practitioners: due to several phenomena (e.g. heat dispersion, border effects, etc. – for more details see section 5), the time for modifying the fluid glass temperature is the shorter, the closer to the main channel the spooling-bushing ma-

² The only elements that could introduce the wear phenomenon would be the spooling machines. However, they are not affected by it because they are not subjected to mechanical solicitations at all.

chine is. However, two exceptions can be identified; as a matter of fact, with reference to the triples 104-106 and 204-206, the above described trend for the parameter 'number of lags to be considered' is not verified. In particular, these exceptions, due to the relatively few historical data used in the evaluation procedure, will probably lead to non-satisfactory results concerning the mentioned triples. Finally, with reference to the values of the parameters reported in table 4, no particular interpretations can be given: actually, they represent the values for which the corresponding EACD model has the most predictive power.

4.4 Experimental campaign and results

The simulation has been introduced firstly to test the effectiveness of the previously defined EACD models in representing the influence of the furnace on the spooling-bushing department. And, as a consequence, to verify if the proposed approach, is helpful to model the relationships between the continuous and the discrete parts of the hybrid production system under study. The physical model of the furnace and spooling-bushing department system has been built through the event-driven meta-language ARENA (Kelton *et al.* 2002). Since the goal is not to test management policies for containing the fibre-breakings effects, in the experimental campaign no alternatives concerning the decision variables are considered (decision variables are given by the number of operators assigned to solve fibre-breakings and by the production rate of each spooling-bushing machine. As a matter of fact, both of them do not have any influence on the fibre-breakings occurrence but on their effects only). The context, the experimental campaign deals with, is implicitly given by the wearing-out phase of the furnace (actually, the study described in this section has been performed during the end of the furnace life-cycle). Even if one context only is taken into account in the experimental campaign, no problems seem to rise due to the independence of the fibre-breakings phenomenon from the time factor (see paragraph 4.3). Concerning the inputs of the model, the idea was to run the latter in two different conditions: (i) the fibre-glass breakings occurring on each triples of adjacent spooling-bushing machines are generated according to the EACD models (see table 3); (ii) historical fibre-glass breakings data are used. The comparison between the simulation results under the EACD model and the results obtained under the historical data, leads to prove the effectiveness of the proposed approach.

Since the fibre breakings occurrence has an impact on the spools weight (see paragraph 4.1), the variables chosen as benchmarks for the comparison were the daily throughput of the furnace and spooling-bushing department system in terms of completed spools (i.e. 32 kg spools) and the weight of the uncompleted spools (see paragraph 4.1). The variable referring to the completed spools is treated by means of parametric statistical tools, whereas the weight of the uncompleted spools is considered as an empirical distribution of probability and thus it has to be treated with instruments belonging to the non-parametric statistics.

Under the model where the fibre breakings are represented by the EACD specifications, the experimental campaign consisted of 10 simulation runs, each of them characterized by a six-day length (i.e. 518 400 seconds, being the second the time unit of the model. Six days are a sufficient amount of time for a significant evolution in the fibre-breakings occurrence, given the high frequency of the breakings phenomenon). The simulation model of the furnace and the spooling-bushing department does not seem to be affected by a transient period; however, in a precautionary way, only outputs from the 2nd to the 6th day have been considered in the statistical analysis. Under the model fed with breakings historical data, the

simulation run length has been determined by the need to have a sample data different from the one used to estimate the EACD specification, and the experimental campaign has consisted in a 12-day simulation run characterized by a one-day warm-up period.

The statistical analysis has been performed in two ways. First, for each spooling-bushing work-centre, the 95% t-Student (Greene 2000) confidence intervals for the daily throughput in terms of completed spools, have been compared to the mean value and standard deviation of the daily throughput calculated from the model fed with historical data. The expression used to obtain the confidence intervals is given by:

$$\mu_z \pm t_{z-1,h} \cdot \sqrt{\frac{S^2(z)}{z}}, \quad (12)$$

where μ_z is the average value of the z observations and t , according to the Student's distribution, equals to 1.83, given $z = 10$ and $h = 0.95$. Second, the empirical probability distributions of the uncompleted spools weight under the EACD-based simulation model and under the model fed with historical data have been compared using the Smirnov test, a non-parametric test derived from the Kolmogorov – Smirnov test, which allows the hypothesis that two data sets belong to the same unknown (and usually empirical) distribution to be verified. In particular, the statistics of the test is:

$$D_{n,m} = \max |F_{1n}(x) - F_{2m}(x)|, \quad (13)$$

where F_{1n} and F_{2m} are the two empirical distributions (n and m are the sizes of the data samples) and the null hypothesis is that $F_1 = F_2$, that is the two data sets have been extracted from the same probability distribution. For high values of n and m (usually greater than 100), the null hypothesis can not be rejected if:

$$D_{n,m} < \sqrt{(n+m)/(n \cdot m)} \cdot k_{1-\alpha}, \quad (14)$$

where α is the probability of the excluded tails. Typical alpha values are 0.01, 0.05, 0.1, 0.15 and 0.2 and the corresponding $k_{1-\alpha}$ values are 1.63, 1.36, 1.22, 1.14 and 1.07 respectively (to deepen the Smirnov test, refer to Greene (2000)). Table 5 presents a synthesis of the experimental campaign.

Experiment	Decision variables	Context	Input	Number of runs	Run length	Warm-up period
1	Operators number [2] Machines production rate [std]	Furnace ware-out period	Fibre-glass breakings generated according to EACD models	10	6 days	1 day
2	Operators number [2] Machines production rate [std]	Furnace ware-out period	Historical fibre-glass breakings data	1	12 days	1 day

Table 5 – Synthesis of the experimental campaign

Table 6 and figure 8 present a synthesis of the statistical analysis: the first two columns of the table allow the comparison between the average values of the daily throughput, whereas the others are devoted to the non-parametric test. Notice that the 95% confidence intervals for the daily throughput obtained from the 10 replication runs of the simulation model based on the EACD specifications match quite well the corresponding intervals given by the average values with the standard deviations of the same variable calculated by experimenting on the simulation model fed with historical data (on this subject, see also figure 8 that graphically shows the first two columns of the above mentioned table).

Machine	Daily throughput		$D_{n,m}$	Smirnov threshold	Alpha
	Simulation model fed with historical data	EACD-based simulation model			
101	39.36±4.01	38.02±4.49	0.089994	0.115786	0.20
102	36.00±7.11	36.22±5.01	0.055627	0.114168	0.20
103	34.54±5.26	32.96±3.34	0.082719	0.105877	0.20
104	72.64±8.95	71.70±3.21	0.082430	0.082655	0.20
105	62.45±9.07	60.70±5.36	0.107105	0.121636	0.01
106	62.09±7.34	61.92±4.90	0.054851	0.090238	0.20
107	63.73±8.40	64.54±6.02	0.051799	0.084201	0.20
108	61.27±6.13	60.38±5.60	0.083758	0.099649	0.05
109	63.09±8.94	63.52±6.61	0.044253	0.073513	0.20
110	33.00±6.42	33.00±5.05	0.126288	0.131860	0.01
111	43.91±7.82	45.56±8.21	0.130047	0.124017	0.01
112	42.09±1.81	42.46±2.52	0.069624	0.153942	0.20
201	38.54±3.42	38.68±1.62	0.063226	0.108842	0.20
202	45.91±2.70	44.88±2.40	0.111433	0.133450	0.05
203	46.91±4.46	46.96±1.87	0.093188	0.105216	0.20
204	68.64±9.59	67.40±4.98	0.051941	0.064498	0.20
205	67.73±4.03	63.96±4.92	0.113079	0.127671	0.01
206	64.27±4.96	63.64±3.23	0.114678	0.114811	0.05
207	56.09±11.1	55.20±7.09	0.050125	0.064585	0.20
208	58.36±10.5	54.28±8.72	0.109315	0.092534	0.01
209	41.27±4.15	40.00±4.68	0.073805	0.073970	0.20
210	36.82±3.87	35.54±4.00	0.067347	0.071405	0.20
211	28.27±10.5	24.04±4.02	0.072063	0.075672	0.05
212	24.45±8.62	21.86±3.39	0.145297	0.109637	0.01

Table 6 – Statistical analysis results

For some spooling-bushing machines (i.e. 104, 105, 106, 204, 205 (as expected, see paragraph 4.3), 208, 211 and 212) this is not completely true. However, two considerations must be taken into account: (i) the fibre breakings phenomenon is inherently uneven and (ii) the difference between the number of observations derived from experimenting on the EACD-based simulation model and on the historical data-based simulation model is quite relevant (i.e. 50 vs. 11 values). The last three columns of table 6 point out that the null hypothesis of the Smirnov test can be rejected for only three spooling-bushing machines out of 24 (i.e. 111, 208 and 212) This means that for only three spooling-machines the two empirical distributions, obtained for the uncompleted spools weight from the EACD-based model and the model fed by historical data, are different.

These results allow to draw two main conclusions, characterized by different levels of generality. First, EACD-based model proved useful for representing, in the context at hand, the occurrence of fibre-glass breakings on the spooling-bushing machines; second, since the fibre-glass breakings are a particular type of minor stoppages, the methodology based on the ACD specifications proposed in section 3 could be really suitable for the logical modelling of the hybrid production systems where the relationships between the continuous and the discrete parts are given by the occurrence of minor stoppages.

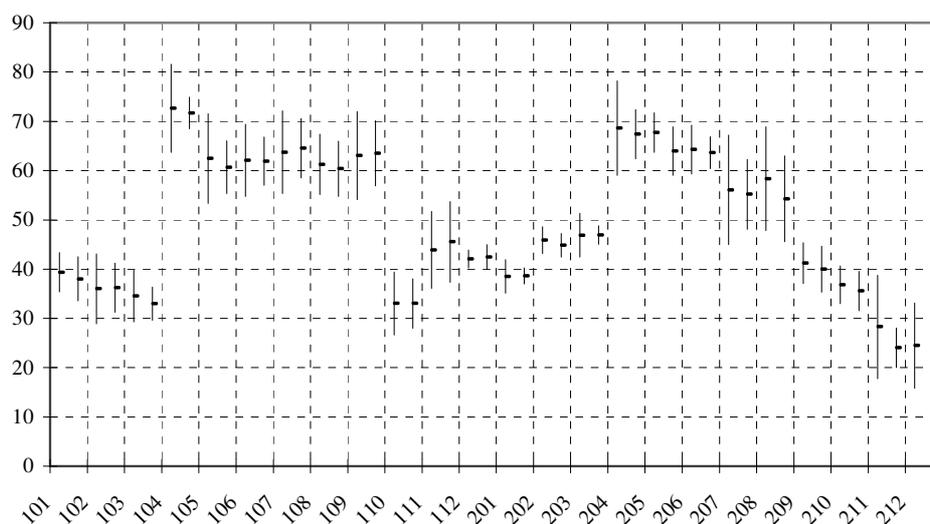


Figure 8 – Graphical comparison among daily throughput intervals

4.5 Comparison with other approaches

Unlike the proposed approach, the ones listed in table 1 could not be proved so effective in representing hybrid production contexts. As example, figure 9 shows the model based on the hybrid Petri nets formalism of the system presented before.

In short, places P1, P2 and P3 and transitions T1, T4, T5 and T8 models the temperature dynamics of the fused-glass pouring into a generic spooling-bushing machine. In particular, given the initial mark, the continuous transition T1 is activated and modifies the value of the continuous variable x (fused-glass temperature) according to the differential equation $\dot{x} = \xi_i(t)$. The fused-glass temperature is recorded in P2, which is linked, by means of test arcs, to several discrete transitions. If certain conditions are verified (these conditions should involve both the magnitude and the derivative of the fused-glass temperature) the transition T2, T3 or T4 becomes active. The first two transitions assign to the attribute 'state' of the token in P4 the value 'W' (wasting), whereas T4 causes the cancellation of the token in P1 and the creation of 1 token in P3 allowing for the activation of T5. In other words, T4 models the autonomous switching phenomenon (transitions T5, T6, T7 and T8 are equivalent to transitions T1, T2, T3 and T4 respectively).

With reference to the second part of the Petri net, transition T9 (activated by the value 'S' (spooling) of the attribute state of the token in P4) modifies, according to the differential equation $\dot{p} = \rho$, the coil's weight recorded in P5 (ρ is the machine's rate in kilos per time unit), whereas transition T20 (activated by the value 'W') updates, in P18, the overall amount (w) of the fused glass wasted because of fibre-glass breakings.

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The other places and transitions describe the spooling-bushing machine dynamics.

According to this model, the temperature evolution should be represented by means of a set of differential equations (i.e. $\dot{x} = \xi_i(t)$, see transaction T1) but the definition of realistic vector fields in the case of the furnace and the spooling-bushing department sub-systems is practically impossible, due to the hurdles risen in quantifying the effects on the temperature (i.e. the continuous variable x) of all the parameters which have an influence on it. More in detail, the vector fields should take into account the contributions of at least 9 factors (see table 7) to the fused glass temperature dynamics. To quantify the impact of each factor (reported in table 7) on the vector fields is an extremely complex issue. Complexity is further increased by the offset between the generic time for which the vector fields have to be calculated, and the time when the influencing factors have occurred, i.e. $\xi(t)$ depends on the amount of raw materials introduced in the furnace at time t_i (with $t_i < t$), on the quantity of gas and air mixture introduced in the furnace at time t_j , (with $t_j < t$) etc., and the number of lags $(t - t_i)$, $(t - t_j)$ etc. is neither *a priori* known nor practically feasible to be determined. Moreover the hybrid Petri nets formalism (as well as the other traditional approaches) is supposed to represent the controls on the temperature (i.e. the continuous variable x) allowing the autonomous switching (i.e. the switching from $\xi_i(\cdot)$ and $\xi_j(\cdot)$ and *vice versa*) and the autonomous jumps (i.e. the fibre-glass breakings and, as a consequence, the changes in the spooling-bushing machine state) to be modelled. However, the conditions which activate switching and jumps are difficult to be pointed out, since they depend on both the temperature value and the temperature derivative of the fluid mass pouring in the spooling-bushing machine. In other words, the fibre-glass breakings can be caused by either an excessive temperature of the fused glass (that corresponds to a too liquid fluid mass), or by a too low temperature (that corresponds to a too solid fluid mass), or even by particular combinations of temperature and temperature change rates. As a consequence, the only way to model the furnace and spooling-bushing department system by means of the hybrid Petri nets formalism (and, in more general terms, by means of the formalisms belonging to the other traditional classes of either automata and transition systems, or dynamical systems) lies in: (i) making a great simplification of the vector field, by considering only the effects of the amount of raw materials and combustible mixture introduced in the furnace and an offset time constant and *a priori* known; (ii) disregarding the autonomous switching phenomenon, because of the impossibility to adequately represent the effects of the secondary channels burners on the fluid mass temperature; (iii) verifying only conditions concerning the temperature, thus overlooking the combinations of temperature and temperature change rate (see places P1, P2 and P3 and transactions T1, T4, T5 and T8). However, the model outlined above is so different from the real-life system to prevent from a correct representation of the relationships between furnace and spooling-bushing department, i.e. the effects of the continuous part of the system on the discrete one neither in terms of number of fibre-glass breakings nor in terms of breakings frequency. Exactly these hurdles prove the need for a new approach for modelling hybrid production systems and, therefore, the theoretical relevance of this study and of the presented results.

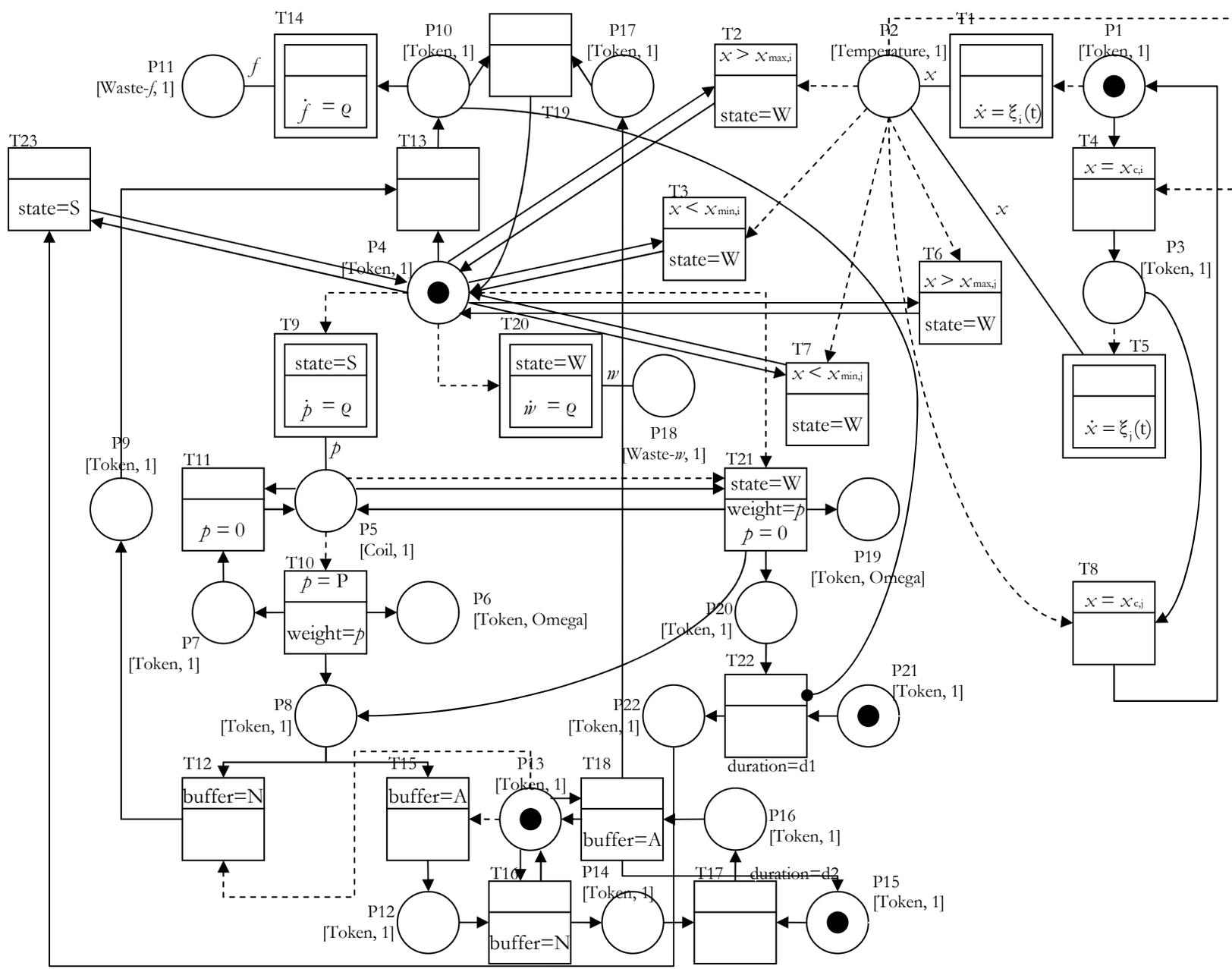


Figure 9 – Hybrid Petri nets of the described production context

Factor	Effects
Amount of raw materials introduced in the furnace	Raw materials, entering at the room temperature, represent a negative heat flow whose consequence lies in reducing the value of x . The effect of this heat transfer is not uniformly distributed: the closer the fluid mass to the raw material input area, the higher the negative effect on the temperature is.
Amount of gas and air mixture introduced in the furnace	Gas and air mixture represent a positive heat flow: the oxygen, due to the temperature inside the furnace, allows the mixture to be burned immediately after it has been introduced. This heat transfer is space-wise uniform, but uneven over time, since several intake points are distributed along both sides of the furnace. Moreover, it has a double effect: it contributes to the direct heating of the fluid mass and to heat the roof of the furnace
Irradiative heat flow from the furnace roof	This heat flow is probably the main factor that positively influences the fluid mass temperature: since the roof is not flat and its temperature is not uniformly distributed neither space-wise nor time-wise, each elementary unit of fused glass going out of the furnace cannot have received the same amount of irradiative heat.
Action of burners placed on the furnace floor	These burners can be turned on to minimize the temperature gap between different layers of the fluid mass. Their switching on depends on the temperature of the lowest layer of the fused glass.
Convection of the fluid mass in the furnace and in the channels	The convection should contribute to uniform the temperature of the different layers of the fused glass, by carrying out an action similar to the one of the burners.
Heat dispersion in the (main and secondary) channels	The fluid mass that passes through the channels transfers heat to the channels walls, thus reducing the fluid temperature.
Action of burners placed on the secondary channels	Depending on the temperature of the fused glass pouring in a certain spooling machine, the closest burner can be activated or deactivated.
Spooling machine temperature	The spooling machine is gone all over by current which influences its temperature and, in particular, the temperature of the grille, i.e. the specific component of the machine, which the fused glass goes through. Depending on the grille temperature, the heat transfer from the fluid mass to the spooling machine is different and – as a consequence – the temperature of the pouring fused glass changes in a different way.
Spooling machine position	The heat dispersion in the secondary channels depends on the spooling machine position: in particular, the temperature of the fluid mass pouring in the extreme spooling machines is affected by border effects.

Table 7 – Factors influencing the fused glass temperature vector field and their impacts on it

5. Conclusions

The traditional approaches developed in literature for modelling hybrid systems have been applied to contexts whose continuous and discrete parts are synchronous and characterized by level-variables (Wieting, 1996). However, the elements a production system is composed of (i.e. queues, operative buffers, etc.), make the system asynchronous and the continuous variables characterizing a production environment are not necessarily level-variables. For these reasons, the main aim of the study consists in identifying a methodology for modelling hybrid production systems where the relationships between the continuous and the discrete parts are given by minor stoppages.

The suggested approach is based on the Autoregressive Conditional Duration (ACD) models, originally conceived to treat high-frequency and irregularly spaced transaction data, and it has been applied to an industrial case belonging to the fibre-glass reels industry. More in detail, the Exponential ACD (EACD) model has been employed to represent the interactions between the furnace and the spooling-bushing department. These interactions, given by the fibre-glass breakings due to the dynamics of the fluid mass temperature, are very similar to the transaction data of the stocks market, since they are very frequent (i.e. there are hundreds of breakings per day), irregularly spaced and characterized by the clustering phenomenon (i.e. short and long durations are followed by short and long inter-arrival times respectively).

The usefulness of the proposed approach has been proved by building, according to it, the logical model of the furnace and spooling-bushing department system and by testing the model through simulation. The outputs of the experimental campaign have been compared to the outputs obtained by feeding the same model with real fibre breakings historical data. In particular, the outcomes of the comparison allowed not only the logical model of the context under study to be validated, but also the proposed approach to be identified as a possible method to represent generic hybrid production systems where the relationship between continuous and discrete parts is given by minor stoppages.

Of course, this last statement should be more deeply verified: for this reason several case studies belonging to industries different from the fibre-glass sector have been planned. In addition to this extension of the ACD-based modelling methodology, future research steps deal with additional studies of the context treated. These analyses are aimed, on one hand, at using non-linear ACD specification to improve the model suggested here **and at investigating the integration of the model with the fuzzy logic (which could allow either automatic expert systems to be developed (Zimmermann, 1991), or data affected by uncertainty and vagueness to be considered (Zadeh, 1965), or effects of controls to be introduced (Yuniaro and Labib, 2005))** and, on the other hand, at applying multi-variables ACD specification and spatial statistics to verify the practitioners' hypothesis according to which the fibre breakings at each work-centre (i.e. a triple of adjacent spooling-bushing machines) are single and independent stochastic processes.

The innovative contribution of the proposed approach is that it is twofold. On one hand, it represents, through the ACD specification, the relations among the continuous and discrete parts of a system, i.e. it represents a hybrid system by means of a discrete abstraction based on an econometric model (at present, methods for modelling hybrid systems given by discrete abstractions already exist; however, they are very complex and hard to be imple-

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mented since they require that all the possible statuses of the system, as well as all the possible status changes are identified and represented through algebraic matrixes (Rossi, 2004)).

On the other hand, the proposed approach is the first one specifically developed for hybrid production systems and, as a consequence, the first really suitable for such kind of systems. Actually, as mentioned before, the majority of approaches found in literature – and listed in table 1 – have been developed for and applied to physical hybrid systems only.

With reference to the limits of the proposed approach, the first one is given by the fact that it requires the evaluations of the memory steps the selected ACD model must be provided with, as well as of the values of the model parameters. Actually, the evaluation procedure is quite complex since statistical tools specifically designed to deal with the ACD specification do not exist yet. As a consequence, to perform the evaluation phase, which is absolutely necessary for the proposed approach, *ad hoc* application programs must be realized and, overall, the log-likelihood functions of the considered ACD models must be defined (moreover, to correctly perform the evaluation phase, a very large number of historical data is needed. For example, as concerns the case study presented in the paper, about ten thousands fibre breakings durations have been recorded to allow for defining the number of memory steps and the parameters values characterizing the ACD model of each spooling-bushing machines triple). The second limit is represented by the fact that the proposed approach can be used only for modelling hybrid production systems where the relations among the continuous and the manufacturing parts are given by minor stoppages. Actually, the ACD specification is conceived to treat high-frequency and irregularly spaced transaction data and, as a consequence, is not suitable at all for modelling the occurrence of sporadic events.

In conclusion, notwithstanding the above-mentioned limits, the proposed approach can prove really useful even in practice: the company whose production system has been referred to in the paper is a very relevant business in the world-wide sector and requested, for one of its Italian plants, a simulation model built disregarding the furnace and representing its effects on the spooling-bushing department through an ACD model. Now the simulation model is employed in the field as a decision support tool for both design and management purposes.

In particular, an appropriate representation of the effects of the continuous part of the system on the discrete one in terms of number of fibre-glass breaks as well as in terms of break frequency, allows the company to define both the production capacity required downstream at the spooling-bushing department (that is the model is useful to face a production planning problem) and the number of operators to be assigned to the fibre breaks solving activity (that is the model is useful to face a crew assignment problem).

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