Model Predictive Control of a Conveyor-Based Drying Process Applied to Cork Stoppers

Pedro Tavares, Tatiana M. Pinho, José Boaventura-Cunha and António Paulo Moreira

Abstract Control applications are a key aspect of current industrial environments. Regarding cork industries, there is a particular process that needs to be addressed: the cork stoppers drying. Currently the methodology used in this process delays the overall production cycle and lacks in the drying efficiency itself. This paper presents the development of a cork stopper drying system based on the control of a conveyor based machine using Model Predictive Control (MPC). Throughout the project it was also developed a drying kinetics model for the cork stoppers and an extension of such model to a discrete space state model. By applying the proposed methodology it is assured the cork stoppers' drying in a faster and more efficient way.

Keywords Model predictive control · Industrial drying · Modelling · Cork stoppers · Conveyor-based system

1 Introduction

Drying operations have become one of the industrial key steps in several products development. Therefore, the scientific and research community has shown interest in develop drying solutions to improve the efficiency in several processes. The ambition of obtaining streamlining industrial drying operations has led to the developed of specialized solutions in several industrial areas [9]. In particular, the cork-based industry has strict requirements concerning moisture levels and the drying process efficiency. Generally, cork-based products are realized in a complex production chain [10]. Despite cork can be used to produce several products, in order to maximize raw

P. Tavares (✉) · T.M. Pinho · J. Boaventura-Cunha · A.P. Moreira
INESC TEC - INESC Technology and Science, Porto, Portugal
e-mail: pedro.ms.tavares@gmail.com

P. Tavares · A.P. Moreira
FEUP - Faculty of Engineering of University of Porto, Porto, Portugal

T.M. Pinho · J. Boaventura-Cunha
UTAD - University of Trás-os-Montes and Alto Douro, Vila Real, Portugal

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material use, the first transformation objective is to develop natural cork products. Among these, cork stoppers represent the biggest portion of cork industry [6].

Considering these premises and the ever-growing need to maximize the efficiency in drying operations, there is an evident interest in developing drying methods and machines for cork stoppers. These products need to present moisture contents levels below a pre-defined fixed value. Although there have been studies regarding the kinetics and dynamics of the drying operation in multiple areas (including cork stoppers [2, 8]), lately the goal is to maximize the efficiency of the drying operation regarding the time and energy consumption.

In this paper, it will be presented a generic control approach, that, due to its flexibility, has potential to be applied to any drying scenario using conveyor-belts. It will also be proposed the modelling of the cork stopper drying process and a new model predictive controller designed for this application. The main goal of this approach is its integration in the cork stoppers production line, allowing the optimization of the plant layout reducing delays in the production, with the guarantee of the requirements in the moisture content level in less time.

The current paper is structured in five main sections. Section 2 aims to provide an overview of the evolution in drying process optimization approaches. Section 3 (System Architecture) describes the developed approach to solve the proposed problem. Within this section are also described the developed modelling and control architectures. Section 4 (Experimental Validation) synthesizes the results obtained by the developed system in both simulated and real environments. Section 5 (Discussion and Future Perspectives) reviews the contribution of this project to the scientific world and points some issues for improvements.

2 Related Work

The control architecture development in industrial environment is associated with the scientific and technological development. Currently, drying solutions can be classified as static or dynamic. The first one considers that the product of interest is fixed above a flat bed dryer. The conventional flat bed dryer has the problem of producing nonhomogeneous drying results. Thus, the second approach considers that the product is moved throughout the process trying to create homogeneous results. There are several examples of this type of approach that allows the maximization of the drying efficiency [3, 12].

Focusing on the dynamic drying processes, one of the major contributions is the use of conveyor-belts design to increase the process quality. In 2008, Zanoelo et al. proposed to reproduce the drying kinetics in a continuous shallow packed bed dryer of mate leaves at transient conditions by adjusting the conveyor-belt velocity to compensate disturbances in the operating conditions [13]. Years later, in 2015, Alamia et al. proposed an integrated dryer and conveyor belt for woody biofuels with steam as the heat transfer medium [1]. This approach can be valuable as it achieves higher energy and exergy efficiencies. Furthermore, there are recent studies that consider drying methods, such as micro waves, with enough energy to remove completely the moisture from a product [7]. However this technique can degrade some properties of the material and can not be applied to all drying processes. Currently the removal of moisture from the cork stoppers is assured by placing these within drying chambers. In this context, drying chambers replacement for a new drying method proves to be beneficial as the time and energy consumption related to the drying of cork stoppers in drying chambers creates a delay in the production as well as excessive energy expenditure.

Although all strategies presented have been implemented and validated in the industrial world they have limitations when applied to cork stoppers drying and thus considerations must be taken for each given application.

3 System Architecture

The proposed system is a flexible model predictive controller capable of assuring the drying of cork stoppers in multiple conditions with a conveyor-belt based solution. As such in this section it will be presented the main tiers of flexible control application: modelling and discretization (Sects. 3.1 and 3.2) and control and actuation methodology based on the developed model (Sect. 3.3).

3.1 System Modelling

Throughout the drying process it were considered four types of state variables, namely the temperature and humidity of both cork stoppers and the surrounding environment air. Previous works state that the evolution of these variables is expressed as a set of equations (see parameters list in Table 1) [4].

The drying process is essentially defined as an exchange of water between the product intended to dry and the surrounding atmosphere. As such, it can be represented by a mass variation between the product M_p and the air M_a, see Eq. 1.

$$\frac{\partial M_p}{\partial t} = \delta_m \quad \& \quad \frac{\partial M_a}{\partial t} = -\delta_m \tag{1}$$

There is a grounded relation between mass and humidity values. The mass variation is directly connected to the humidity variation in the cork stopper (α) by a multiplier factor.

$$\frac{\partial M_p}{\partial t} = K * \frac{\partial \alpha}{\partial t} \tag{2}$$

Table 1 Parameters involved in the drying process

Parameter	Parameter specification	Unit
δ_m	Drying rate	$\frac{kg}{s*m^3}$
ρ_a	Air density	$\frac{kg}{m^3}$
λ_0	Latent heat of vaporization at the atmospheric pressure	$\frac{J}{kg}$
R_v	Individual air constant	$\frac{J}{kg*K}$
β	Dry air specific mass ratio	–
T_{dp}	Dew point temperature	K
T_0	Triple point temperature	K
P_{atm}	Atmospheric pressure	Pa
$P_{s,0}$	Partial pressure at the reference temperature	–
ζ	Falling rate multiplier of the drying rate	–
h	Heat transfer coefficient	$\frac{W}{m^2*K}$
ϵ	Evaporation area over product volume ratio	$\frac{1}{m}$

The proposed solution runs in a conveyor-based platform. As such there is the need to add a term in the direction of movement (x, for the cork stoppers and z, for the air). Due to the architecture used in the machine construction there will be three air temperature and humidity measurements and, thus, eight global variables.

Concerning the drying systems modelling, there are works defending the need to establish a threshold for the product minimum humidity value [5]. In this particular case, the cork stoppers minimum humidity value is 5 %. However, at the drying step it is required only a mean humidity of 7.5 %. Furthermore, attending to the developed hardware solution that is going to be used, there are some assumptions and simplifications to consider:

- The cork stoppers are evenly distributed on the conveyor-belt.
- The height at each section is the height of a single cork stopper.
- The volume shrinkage of the cork stopper is negligible.
- All mass lost in the cork stopper is only due to the humidity evaporation.
- The heat losses from the machine interior to its exterior are negligible.
- It is assumed constant pressure throughout the different conveyor-belt zones.
- Densities, specific heat capacities and evaporation/volume ratio are constant.
- The velocity of the hot air that promotes the drying process is constant.

The model described by the initial equations is clearly non-linear since it is mostly defined using partial differential equations. As such a way to simplify this model is by using a finite difference approximation. In this way it is possible to separate the model in small blocks that allow implementing an approximation to the partial differential equations.

Considering one infinitesimal section travelling throughout the conveyor at each iteration we can take into consideration only the variation of humidity with time $\frac{\partial \alpha}{\partial t}$ (bypassing the term dependent of the distance travelled, $v_x * \frac{\partial \alpha}{\partial x}$).

Another modelling aspect is related to the temperatures variation. In this particular project the objective is to maintain the heating temperature constant. As such the air temperature variation ($\frac{\partial T_a}{\partial t}$) is zero. As a result of fixing the heating temperature constant, the cork stoppers' temperature will only depend on the thermal conductivity of cork (C_c) (or the cork to air thermal resistance R_{ac}) and on the temperature difference between the air and the cork stopper. Based on these considerations it is possible to obtain a single difference equation to express the previous presented state variables evolution, cork stopper humidity α and temperature T_p and air humidity γ.

$$\frac{\partial \alpha}{\partial t} = (\alpha - \alpha_e) * K * \delta_m \ \ \& \ \ \frac{\partial T_p}{\partial t} = C_c * \frac{T_a - T_p}{R_{ac}} \tag{3}$$

$$\frac{\partial \gamma}{\partial t} = -\frac{1}{K} * \frac{\partial \alpha}{\partial t} * \frac{1}{\rho_a * v_z} \tag{4}$$

Finally, in order to apply this model, is mandatory to define the drying rate, δ_m. This value can be calculated using the following equations [4]:

$$\begin{gathered} T_{dp} = ((\frac{1}{T_0}) - ((\frac{R_v}{\lambda_0}) * log(\frac{P_{atm} * \gamma}{\rho_{s,0} * (\beta + \zeta)})))^{-1} \\ \zeta = \frac{0.9}{\alpha_{crit} - 0.02} * \alpha + \frac{0.9}{\alpha_{crit} - 0.02} * \alpha_{crit} \ \ V \ \ \zeta = 1 \\ \delta_m = \frac{h * \epsilon}{\lambda_0} * (T_{dp} - T_a) * \zeta \end{gathered} \tag{5}$$

3.2 State Representation Model

Once modelled the process, it is necessary to adapt its formulation in order to become faster in computational processing. As such it was chosen a non linear space-state representation model defined as:

$$\begin{aligned} x_{t_{k+1}} &= f(x_{t_k}, u_{t_k}, \alpha_e) \\ y_{t_k} &= C * x_{t_k} + D * u_{t_k} \end{aligned} \tag{6}$$

In state models representation, x_{t_k}, u_{t_k} and y_{t_k} are respectively the state, the control variables and the output in a given instant t_k.

$$x_{t_k} = [\alpha_{t_k}; T_{pt_k}; \gamma_{zt_k}; T_{azt_k}]' \ \ \& \ \ y_{t_k} = \alpha_{t_k} \tag{7}$$

Fig. 1 Real machine and zones 1 in *red*, 2 in *yellow*, 3 in *blue*

α_{t_k} and T_{pt_k} represent, respectively, the cork stopper humidity and temperature in the time instant t_k while γ_{zt_k} and T_{azt_k} correspond to the air humidity and temperature values in the zone 1, 2 or 3 (see Fig. 1) where the infinitesimal section of cork stoppers is in that instant. Besides these zones, there is also a stabilizing zone that is not monitored (green zone in Fig. 1).

Another important structure that we need to consider is the system input at each instant t_k, u_{t_k}. Namely, we have the control variables (v_x and the activation of the boost heater (present in zones 2 and 3)). As such we can define:

$$u_k = [\frac{1}{v_x}; boost_{on}]^T \tag{8}$$

During the process there are also measured variables (air temperatures and humidities in several zones). These variables are important as they allow the controller to estimate the cork humidity and to send a feedback and correct prediction errors. Finally there is an important consideration to have in order to recreate the drying model that is the minimum threshold for the humidity value, α_e (5 %). The controller can be described by the block diagram presented in Fig. 2.

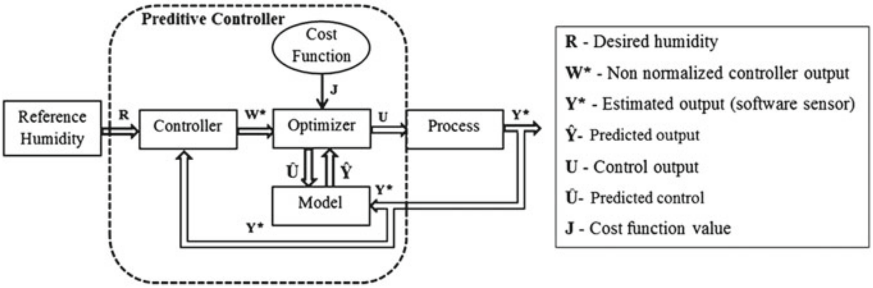

Fig. 2 MPC controller diagram

Furthermore the "Model" block in Fig. 2 is responsible for representing the equations of the drying system. That is, it is the block responsible for the space state implementation. The state representation function and matrices C and D were defined considering a space discretization so that in each section of space there is a corresponding set of parameters values (see Eq. 9). Moreover, based on the space discretization, there is the possibility of considering a variable temporal step dependent of both space and control velocity ($\delta_t = \frac{\delta_x}{v_x}$), where δ_t is the difference of time instants ($t_{k+1} - t_k$). Finally it was used the finite difference method for the discretization.

$$
\begin{aligned}
\alpha_{t_{k+1}} &= (1 + \delta_t * K * \delta_m) * \alpha_{t_k} - \alpha_e * \delta_t * K * \delta_m \\
T_{pt_{k+1}} &= 1 - \frac{\delta_t}{R_{ac}} * T_{pt_k} + \frac{z * \delta_t}{R_{ac}} * T_{azt_k} \\
\gamma_{t_{k+1}} &= \gamma_{t_k} - \frac{-z * \delta_t * \alpha_{t_k}}{K * \rho_a} \\
T_{azt_{k+1}} &= c_z * (MaxTemp - T_{azt_k}) * boost_{on} + T_{azt_k} \\
C &= [1\ 0\ 0\ 0]; \quad D = [0\ 0]
\end{aligned}
\tag{9}
$$

One final consideration is related to c_z value. Due to a physical separation of zones implemented in the machine, this value is considered as zero for zone 1 and one for zones 2 and 3 (zones affected by the boost heater).

3.3 Model Predictive Control

The model predictive control is an advanced control method implemented in several industrial applications. The main advantage of this control is the ability to anticipate future states, use future reference evolution and future disturbances for taking appropriate control actions. In the cork stoppers drying process presented in this work, the model predictive control goal is to define the conveyor speed and the necessity of the boost heater, in order to completely dry the cork stoppers inserted in the machine. This is achieved using an optimization procedure that allows minimizing the overall cork stoppers drying time. The sequence of operations of this process is the reading of the initial humidity of the cork stoppers that will be compared to a standard reference (in this case 7.5 %). While the estimated cork stoppers humidity does not reach that goal, the error that come from the comparison between cork stopper predicted and measured humidity will enter the optimization module and new control actions (conveyor velocity and booster) that minimize the cost function will be computed. This cost function can be defined as the weighted sum of three components: the error between estimated humidity at a set of conditions and the established goal humidity, variation of required speed and the activation of the boost (see Eq. 10).

$$Goal : min_{v_{x_k}, boost_{on}} J_k = min(w_1 * H_k + w_2 * (v_{xk} - v_{x(k-1)}) + w_3 * boost_{on}) \quad (10)$$

J_k is the value of the cost function at each iteration, w_1, w_2 and w_3 are the weights for each section of the cost function. The second term is the variation of required belt speed responsible for smoothing the control signal and avoiding oscillations. $boost_{on}$ describes the current activation state of the boost heater and is the term that considers the energy costs. Finally, H_k is the difference between the predicted and the goal humidity of the cork stoppers.

The choice of prediction and control horizons are key aspect when applying model predictive control. Typically, in these controllers, future outputs $\hat{y}$ at each sampling instant t_k, are estimated over a prediction horizon *HP*. For this particular case the HP value is defined as the number of steps remaining until the process' end. In order to keep the system as near as possible to the set point, the cost function is minimized to compute the set of future control actions, u_k, over a control horizon *M* [11]. In this case, a control horizon of 1 step ahead is considered. Only the first control action is actually implemented because at the next sampling instant the process is repeated with updated information (air temperature and humidities that allow to estimate the cork stopper humidity). In this way, it is possible to achieve the desired goal in the minimum time possible or minimizing a balance between time and energy costs.

4 Experimental Validation

The validation of both the model and the developed model predictive controller was done using two approaches. The first one was the simulation of those in MATLAB using the developed model as reference (Sect. 4.1). The second one was the testing of the controller in a real environment (a drying prototype developed throughout the project, Sect. 4.2).

4.1 Simulated Environment

Throughout the simulations, several strategies were evaluated considering different prediction and control horizons. Moreover there were simulated random disturbances in the system evolution in order to evaluate its response. The best results (for a full prediction horizon and a control horizon of one) are described graphically in Fig. 3.

It was verified that using a full prediction horizon (this is considering every step remaining until the end of the process), the desired results can be achieved successfully with less computational effort. Then it were performed simulations with several control horizons in order to determine the most appropriated. When we increase the control horizon, the complexity is also increased and the time spent in the prediction

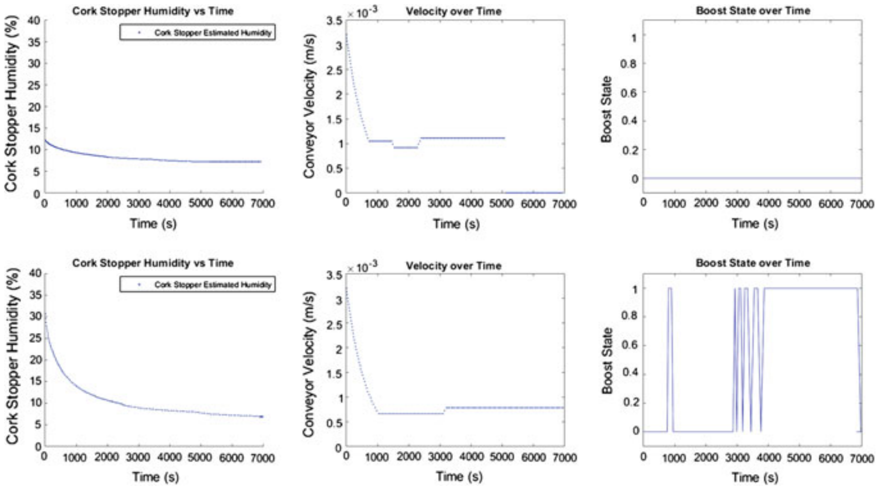

Fig. 3 Simulated cork stoppers humidity and control signals for the best case (at the *top*) and the worst case (at the *bottom*)

reaches a point in which the control is no longer viable for real-time implementation. After some simulations, we conclude that a prediction control horizon of one iteration is preferable for this application in terms of efficiency and complexity, which means that the goal is reached faster and the processing time is lower. This proves to be beneficial since the proposed model is intended to be implemented in a PLC.

4.2 Drying Machine Test

Multiple tests were also conducted using a real machine in order to validate all the modelling and control methods described. We can evaluate the consistency of the developed control strategy by measuring the mass of a set of cork stoppers or using the measurements obtain by the AQUABOY sensor throughout the overall drying process. The complete protocol used was:

1. Choose a set of cork stoppers (in this case fifty) and measure their humidities using the AQUABOY sensor and a precise scale.
2. Pre-heating the real machine until it reaches the stabilization point of 60 °C.
3. Insert the cork stoppers average humidity and quantity in the LCD console in order to update the drying parameters needed to start the process.
4. Place the cork stoppers in the real machine and begin the drying process, activating the movement of the conveyors.
5. At the end, pick the cork stoppers and measure their humidity values.

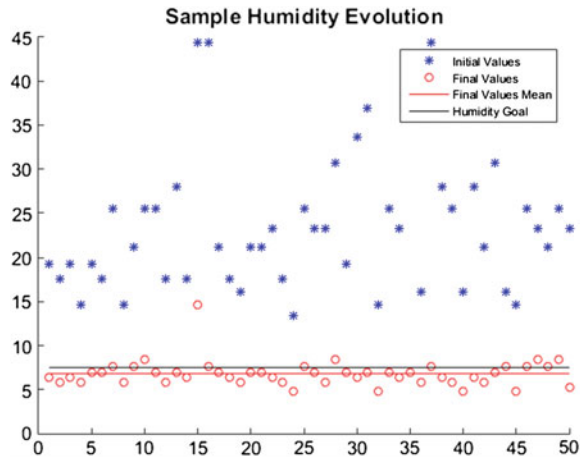

Fig. 4 Set of cork stoppers before and after the drying process

The cork stoppers' humidity can be approximated by a Gaussian distribution. Data from a recent test will be used to exemplify the initial and final humidity of a set of cork stoppers. Initially the mean of this set was 23.5 % with a standard deviation of 7.7 %. At the end the mean was 6.8 % with a standard deviation of 1.5 %. These results are pictured below in Fig. 4. These results represent a recent test using a total of 1500 cork stoppers and monitoring randomly 50 pre-selected cork stoppers.

5 Discussion and Future Work

Throughout this project, it was proposed a model and a controller for the cork stoppers drying process that can be applied to the industrial environment and valuable to the engineering and research community.

One of the most frequent problems associated with drying systems is the nonlinearity of the models that describe the process. This paper presented a structured approach to this issue focusing a particular process, the cork stoppers' drying. There were defined equations for the continuous process and then they were discretized into a space state model so that such equations can be computed in a faster (although precise) way. Another feature of our proposed methodology is the model predictive control layer of our solution. One of the key objectives of the proposed solution was the ability to adapt to several requirements in terms of environment conditions and initial humidity demands. It was proved that the current solution is able to dry the cork stoppers until they reach the pre-determined humidity values (below 7.5 %). Finally, the presented solution feedback was tested in a simulated environment. Currently we are developing a software sensor that can be applied in the real environment. Although this solution shows good results, the proposed approach can be improved. The model developed did not took into consideration a deviation as big as detected with the test in the real prototype. Moreover, it was found that the cork stopper model can not be defined as a simple composition of cork and water. There are some volatiles that influence the mass of the cork stopper that need to be considered. In the future a refinement of the model would be advantageous.

In conclusion, the work presented formalizes a cork stoppers drying approach. This solution can be valuable in several fields of control based on its flexibility as it produces interesting results for any required initial parameters as long as they remain within the pre-determined range of initial values.

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