XXXVIII Jornadas de Automática
https://doi.org/10.17979/spudc.9788497497749.0604

DEVELOPMENT OF A GREY MODEL FOR A MEDIUM DENSITY FIBREBOARD DRYER IN ECOSIMPRO

Pedro Santos Bartolomé, José Luis Pitarch, César de Prada

Dpto. Ingeniería de Sistemas y Automática, Escuela de Ingenierías Industriales, Universidad de Valladolid.
C/ Real de Burgos s/n, 47011, Valladolid. pedro.santos.bartolome@uva.es, {jose.pitarch | prada}@autom.uva.es

Summary

This work contains the design and testing of a grey-box model based on first principles for the drying section of a Medium Density Fiberboard (MDF) manufacturing plant for use in a Model-Predictive Controller (MPC).The fitting of the model to experimental data has been solved with the data reconciliation technique, and the model has then been implemented and tested in simulation for proper behavior. Due to lack of information in a number of relevant process values, as well as low trustworthiness of some measurements, state and disturbance estimators have been determined as necessary to include in the final MPC control schema.

Keywords: MDF, Data reconciliation, Grey model.

1 INTRODUCTION

Medium density fiberboard (MDF) is a wood-based panel manufactured from lignocellulosic fibres by the “drying process”, i.e. having low fibre moisture content at the forming stage and being essentially produced under heat and pressure with the addition of an adhesive [1].

The raw material is chipped and softened by pre-heating in a low-pressure steam boiler, after which it is fed to grinding disks and mixed with adhesive and wax. The mixed product is dried to guarantee low humidity, after which processes of compression, cutting, and heat application are applied to achieve the desired panel properties.

MDF is cheaper than raw wood, more stable, provides a smooth surface for painting, has good machinability and high strength, and is available in larger sizes. Because of this, it is a very popular product that continues to rise in demand, mainly for furniture applications.

Because of the hard requisite of humidity levels, accurate control of the process becomes a necessity. Linear SISO control schemes such as PID loops with decoupling have been usually employed for such a task. However, these controllers do not achieve an acceptable performance during (inevitable) transients due to the nonlinearity and delay of the process. Hence, a nonlinear Model-Predictive Controller (MPC) is considered as more suitable for implementation in one such industry, with this paper concerning the first part of the design: the development of the model.

The proposed model is a grey-box one based in well-known physical relationships between variables, such as mass and energy balances, as well as experimental relationships based on data available, and unknown parameters and variables that will be estimated.

Data reconciliation is used for fitting the model to available experimental data of the plant. Implementation of this task uses the software CasADi [2] in the MATLAB® environment, a modern framework for numerical optimization including automatic differentiation. For analysis of the coherence of the model and final results, the simulation tool EcosimPro® [3] is used.

The paper organizes as follows. Next, a general description of the plant to be modeled. The first principles model is summarized in 3. Then, the customization with experimental data using data reconciliation is formally stated in 4, along with simplifications and experimental equations included in the model. The consistency of the final model and fitness to the data are studied in 5. Finally, a summary of the work together with indications for the next steps in building the controller are given in the last section.

2 PLANT DESCRIPTION

In an industrial MDF wood chips are pretreated as described in the previous section. Due to the low quantity of the additives added to the fiber, that will not significantly impact mass or energy balances, as well as to the inability to obtain useful fiber parameters (width, length, etc.) from the available measurements, this pretreatment has not been explicitly considered in the model. The final mixture of steam, wood chips and additives flows through a steel tube dryer, which is thermally isolated from the environment with a protecting cover of mineral wool.

The air used for drying is procured through an attached fan, and it is a mixture of hot air coming from a heat recovery system, and cold air coming from the environment, both flows meeting in a mixture chamber. The flow of hot and cold air is regulated by the opening of two flaps located on the air paths from the heat recovery and the environment respectively. Both temperature and pressure are known for the hot air inlet and the environment, as well as environmental relative humidity. Air temperatures at inlet and outlet of the tube dryer are also measured.

Once the mixture of air, fibers and additives leaves the tube, it enters a cyclone stage for separation, after which the humidity of the remaining fiber is measured.

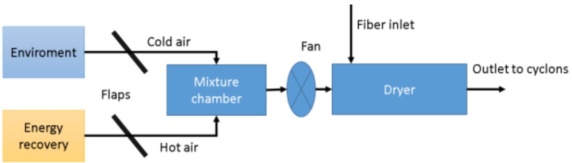

Figure 1: Schematic of the plant.

The final humidity of the wood fiber leaving the dryer is the key indicator of this section of the process, as it greatly impacts the performance of the MDF produced. Therefore the controllers implemented for the plant have to be evaluated by their ability to keep this variable within optimal range during stationary operation and for their reliability to return to these values after large perturbations to the process and product changeovers.

The usual control setup consists of SISO PID control loops controlling important variables such as humidity or temperature by regulating the control variables: percentage of opening of cold and hot air flaps.

This control schema presents several issues, as the process is nonlinear and the involved variables are strongly coupled. Hence, linear SISO controllers are not able to precisely return to their references when a small disturbance arises (operators might be even forced to manually control the process), which, in turn, reduces the quality of the final product.

These circumstances favor the use of a more complex controller capable of predicting these interactions and reacting to changes in the operation with acceptable performance. For this reason a grey model based on first principles is to be developed, with the implementation of a MPC as a final aim.

3 FIRST-PRINCIPLES MODEL

Detailed models of MDF dryers can be found in literature [4], [5]. However, these models involve solving partial differential equations (PDE), which are computationally expensive for online control and optimization purposes. Moreover, the usual residence time of the fibers inside the dryer tube is usually less than the sampling time of data acquisition industrial systems.

Therefore, under the above assumptions, we propose a reduced model for control purposes which avoids the inclusion of partial-differential equations, reducing thus the computational cost significantly in further simulation and optimization stages.

The model is started by formulating the energy and mass balances in the air mixture chamber:

$$F_{in} = F_{amb} + F_{hot} \tag{1}$$

$$F_{in} \cdot H(T_{in}, W_{in}) = F_{amb} \cdot H(T_{amb}, W_{amb}) + F_{hot} \cdot H(T_{hot}, W_{hot}) \tag{2}$$

Where F represents humid air flows in kg/s, H is the specific enthalpy function in J/kg, dependent on the temperature T in ºC and the specific humidity W (mass of water relative to total air mass) with the formula [6]:

$$H(T, W) = 1.006 \cdot T + W(2490 + 1.86 \cdot T) \tag{3}$$

This is followed along with the mass and energy balances of the tube dryer:

$$F_{in} + E = F_{out} \tag{4}$$

$$q_f * X_0 = E + q_f * X \tag{5}$$

$$F_{in} \cdot H(T_{in}, W_{in}) + E \cdot H_w = F_{out} \cdot H(T_{out}, W_{out}) + C_{p\,f} \cdot q_f * (T_{f\,in} - T_{f\,out}) + Q_T \tag{6}$$

Where E is the mass flow of water evaporated in kg/s, q_f is the fiber mass flow in kg/s, X_0 is the inlet humidity of the fiber, X is the outlet humidity of the fiber, H_w is the enthalpy of water at inlet conditions, $C_{p\,f}$ is the calorific power of the wood fiber, and Q_T is the heat loss to the ambient, calculated with the equation:

$$Q_T = \Delta T_M \cdot A \cdot u \tag{7}$$

Where u is the heat transport coefficient, A is the area, and ΔT_M is the average temperature difference between the air and the tube.

It has been shown [4] that the temperature profile in a tube dryer is such that the temperature quickly descends at the entrance. From this follows that the outlet temperature will be dominant to characterize the heat loss to the environment, and so it has been considered exclusively for the lumped temperature difference:

$$\Delta T_M = T_{out} - T_t \tag{8}$$

Where T_t is the mean temperature of the tube whose evolution is calculated with the differential equation:

$$\left(m_t C_{pt} + m_l C_{pl}\right) \dot{T}_t = \Delta_{TM} \cdot A \cdot u - \frac{(T_t - T_l) A_e k}{e_l + e_t} \tag{9}$$

Where T_l is the temperature of the mineral wood isolation, dependent on the heat loss through the tube wall to the environment:

$$\frac{(T_t - T_l)A_e k}{e_w + e_t} = (T_l - T_{amb})A_e u_e \quad (10)$$

Where e_w and e_t are the width of the mineral wool and the dryer tube, respectively.

Finally, the evolution of the humidity of the fiber leaving the cyclones X_f is obtained after a mixture in these cyclones:

$$\tau \cdot \dot{X_f} = X(t - t_d) - X_f \quad (11)$$

Where τ is the time constant of the cyclones and $t_d$is the delay from the fiber entering the dryer until leaving the cyclones.

4 MODEL CUSTOMIZATION

The first-principles model designed would be for valid for any MDF installation with similar structure. After this initial framework, it becomes necessary to further complete the model for the specific TAFIBRA plant, with knowledge available from recorded measurements.

From all variables considered in the above model, measurements are only available for the following:

- Properties of ambient air: T_{amb}, W_{amb}, P_{amb}
- Properties of hot air: T_{hot}, P_{hot}
- Temperature of air at inlet and outlet of the dryer: T_{in} ,T_{out}
- Flow and humidity of fiber leaving the cyclones: q_f,X_f

The following assumptions are made:

1. The relative humidity of the hot air is assumed to be the same as the ambient with no delay. Which along the mass balance of water in the mixture chamber shows:

$$W_{hot} = W_{in} = W_{amb}$$

2. Air and fiber at the outlet are assumed to be in thermal equilibrium

$$T_{f\ out} = T_{out}$$

3. Inlet temperature $T_{f\ in}$ of fiber is assumed to be around 100ºC, as it is boiled before entering the dryer.
4. Inlet humidity of wood fiber X_0 is assumed to be constant. Inlet humidity will evolve slowly with time as the fiber is mixed before entering the dryer.

At this point, the model still has more degrees of freedom than boundary variables, i.e. the manipulated and ambient variables are insufficient to fully determine the system. Thus, in order to fully determine the system, an analysis of the available data has to be conducted with the following goals:

1. Find an experimental relationship between the flow of air and the controlled variables: open percentage of the flaps.
2. Find an experimental formula to adjust the kinetics of water evaporation.
3. Achieve an acceptable fitness of the model to the experimental data.

In order to test the validity of proposed equations (1)-(11) , as well as to adjust unknown parameters of the model, a data reconciliation problem has been performed with experimental data.

4.1 DATA RECONCILIATION

Data reconciliation (DR) is a technique used to obtain values for all process variables according to a model. It relies on the concept of redundancy (duplicated sensors or algebraic constraints) to correct the (possible noisy or faulty) measurements in order to satisfy the process constraints (physical laws) [7]. This step avoids the inclusion of corrupted data (outliers) in further steps, serves as a detector of systematic errors in sensors/process and, possibly, as a parameter estimator.

The fair function estimator [8] is used here as a robust objective function J against measurement outliers and gross errors. Thus, the DR reads:

$$\min_{\hat{\theta}} J(\hat{\theta}, \theta) = \sum_{i=1}^{r} c^2 \cdot \left(\frac{|\epsilon_i|}{c} - \log\left(1 + \frac{|\epsilon_i|}{c}\right) \right) \quad (12)$$
$$\underline{\theta} \leq \hat{\theta} \leq \overline{\theta};\ \ h(\hat{\theta}) = 0$$

Where the i-th error ϵ is calculated as $\epsilon_i = (\hat{\theta}_i - \theta_i)/\sigma_i$, θ are the available process measurements, $\hat{\theta}$ are their estimated values limited between user-defined minimum and maximum values, r is the number of measurements available, $c \in \mathbb{R}^+$ is an user-defined fitting parameter to tune the slope for large residues, and $h(\hat{\theta})$ are the physical restrictions, i.e., equations (1)-(11). Note that, in DR, all model variables are considered as decision variables for the optimizer, with no distinction between input and output.

The optimization problem has been designed and resolved in MATLAB with CasADi [2]. The model is discretized in time via orthogonal collocation to avoid the use of slow numerical integrators to compute the evolution of state variables. Moreover, the cost function $J(\hat{\theta}, \theta)$ is modified to include a penalty for high changes in the algebraic variables between collocation points and a further penalty for changes in the initial and final tube temperature for data sets recorded in stationary operation[1].

4.2 EXPERIMENTAL EQUATIONS

By testing different equations within the data reconciliation problem, the flaps were found to be accurately represented with a relationship between flow and pressure of the form:

$$F = K_v \cdot (0.4 \cdot a + 0.6 \cdot a^3) * \sqrt{P_1^2 - P_2^2} \qquad (13)$$

Where P_1 is the pressure at the inlet of the flap, and P_2 the pressure at the outlet. $P_1 = P_{hot} + P_{amb}$ is considered for the flow of hot air F_{hot}, whereas $P_1 = P_{amb}$ for the flow of ambient air F_{amb}. As both flaps provide the air flows to the mixture chamber, P_2 is equal to the pressure of the mixture chamber P_m (unmeasured) for both. .

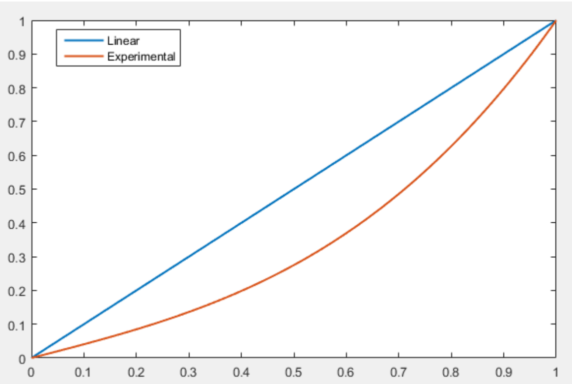

Figure 2: Fraction of flow through flaps as a function of opening signal (blue – linear, red – fitted).

As the outlet of the dryer is at atmospheric pressure, which is measured, the pressure of the mixture can be determined by knowing the pressure increase provided by the fan at the dryer inlet, and the pressure drop due to the friction of the flow through the dryer:

$$P_m + \Delta P_{fan} + \Delta P_{loss} = P_{amb} \qquad (14)$$

The curve determining pressure increase provided by the fan depending on the flow is available from the supplier, and can be accurately fitted with the following quadratic equation (for units of the SI):

$$\Delta P_{fan} = -0.198 \cdot \left(\frac{F_a}{\rho_{air}}\right)^2 - 18.9 \cdot \frac{F_a}{\rho_{air}} + 6.98 \cdot 10^3 \qquad (15)$$

[1] Note that the tube temperature is not measured.

The pressure loss due to friction in the dryer is estimated by the formula:

$$-\Delta P_{loss} = fr \cdot L \cdot D_t \cdot \left(\frac{4 \cdot F_a}{\pi \cdot {D_t}^2 \cdot \rho_{air}}\right)^2 \qquad (16)$$

Where fr is an experimental friction factor.

The development of mathematical models describing moisture movement in wood is a complex mathematical task [9]. In the case of fiber drying, because of the previous chipping of the raw material, complexity is greatly reduced. This benefits the endeavor, as complex mathematical models would make on-line computation unfeasible.

It has been shown experimentally [4] that the speed of water evaporation in a MDF dryer is related to the difference between the dry bulb and wet bulb air temperatures. This relationship varies through the drying process and is affected by unavailable parameters such as fiber diameter, length and initial humidity.

According to the aim of using the model in an online controller, numerical integration of the spatial profiles of variables in the dryer (solving partial differential equations) is discarded for having higher computational cost. Therefore, a simplified experimental equation is looked for fitting the data as much as possible.

A linear relationship between the difference between the dry bulb and wet bulb temperature of the air at the outlet has been found to predict the outlet humidity accurately within the ranges of operation:

$$X = \gamma_1 - \gamma_2 \cdot (T_{Out} - T_{wb}) \qquad (17)$$

Where γ_1 and γ_2 are experimental parameters found by fitting the available data, and T_{wb} is the wet bulb temperature calculated from the outlet temperature and relative humidity [10].

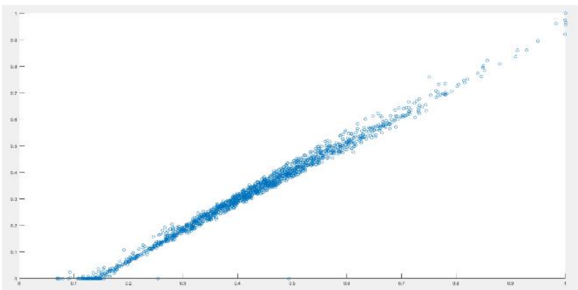

Figure 3: γ_1 vs γ_2 fitted for a range of experimental data.

The analysis of the relationship between γ_1 and γ_2 shows a linear dependency, as seen in Figure 3, but no measured process variable is found to influence their value, linking them to unmeasured variables such as fiber geometry.

Further analysis of the DR results shows the pressure of the hot air inlet as the less trusted measurement for the fitting of the model, as seen in Figure 4and Figure 5, where it can be compared to other input and output variables. As previously said, the data reconciliation makes no distinction between input and output variables, instead using all of them as decision factors to fit the model to the results.

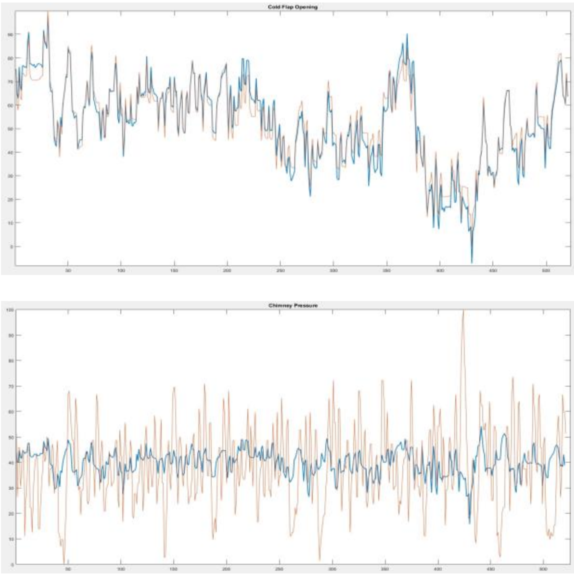

Figure 4: inputs vs fit – up: Ambient Flap, down: Inlet Pressure (red – measurement, blue – reconciled).

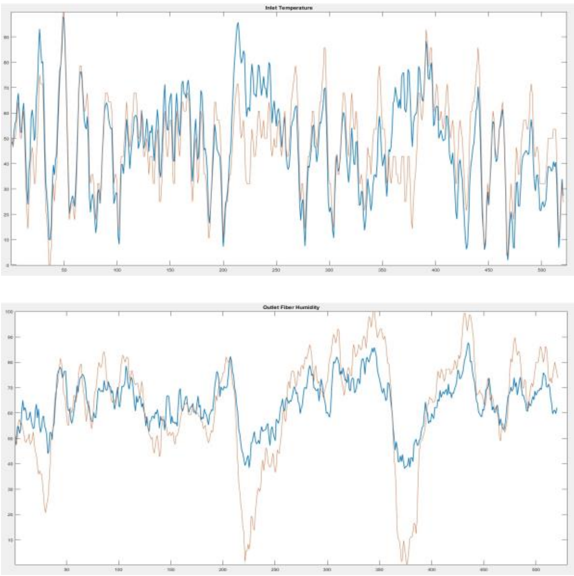

Figure 5: outputs vs fit – up: Inlet Temperature, down: Outlet Fiber Humidity (red – measurement, blue – reconciled).

5 MODEL VALIDATION

Once the model has been closed, i.e. it has as many degrees of freedom as physical boundary variables, the complete model is coded in ECOSIMPRO® [3], a simulation tool for 0D and 1D continuous-discrete systems.

The use of a simulation tool allows for testing of the coherence of the reactions of the model to changes, as well as to analyze the fitness of the model for wide ranges of historic data not included in the DR in the previous section.

5.1 COHERENCE TEST

The first purpose for this simulation is to test the model coherence in different usual situations. Especially for the opening of the flaps, as these are to be the controlled variables by the MPC: if the model predictions to these manipulations are incoherent, the behavior of the controller would be severely compromised.

As shown in Figure 6 and Figure 7 the test for the opening of the flaps shows physically consistent behavior: When increasing the signal to the flap controlling hot air, the volumetric flow of total air increases, as well as the inlet and outlet temperature, whereas outlet fiber humidity decreases. Reverse results for temperatures and outlet fiber humidity are shown when opening of the flap regulating the flow of the ambient air, but the flow of total air is increased as well.

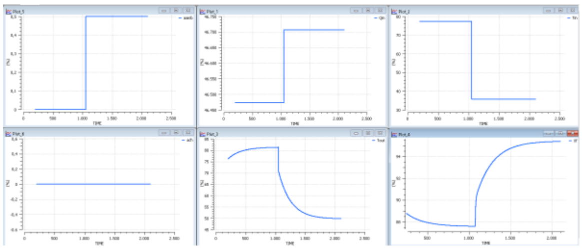

Figure 6: Reaction for increase in open signal of ambient flap. Charts show, from left to right and top to bottom: $a_{amb}, Q_{in}, T_{in}, a_{ch}, T_{out}, X_f$.

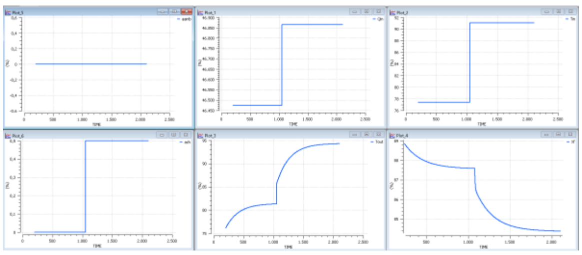

Figure 7: Reactions for increase in open signal of hot air flap. Charts as in Figure 6.

Consistent results are also obtained by testing the other inlet variables such as hot air pressure, atmospheric pressure, inlet humidity or fiber flow. Different values in parameters such as the friction factor and γ_1 and γ_2 are also tested, as the MPC will be implemented with moving horizon estimation to adapt the values of these parameters to fit recent measurements.

5.2 MODEL PREDICTION

After testing consistency, the model with estimated parameters is contrasted with experimental data. The model is shown to consistently produce higher noise in the prediction of inlet air, as shown in Figure 8. This effect is produced because of the high variation and delay of the hot air pressure sensor, which was initially filtered by DR in the model customization phase.

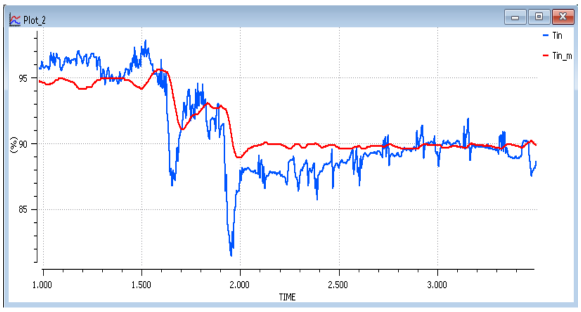

Figure 8: inlet temperature $T_{in}{}^2$ vs time (s). (red - measurement, blue - model).

Both outlet temperature and outlet humidity (linearly related by (17)) show noise inherited from the inlet temperature, as well as due to the influence of the hot air pressure on air flow.

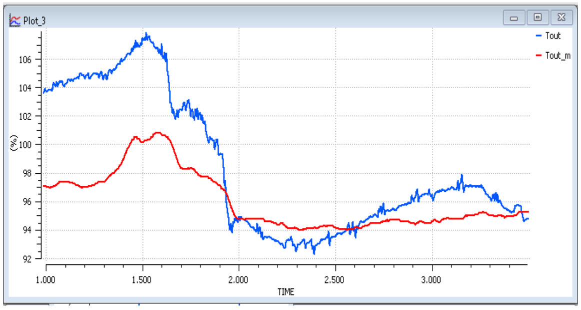

Figure 9: outlet temperature $T_{out}{}^2$ vs time (s). (red - measurement, blue - model).

Significant differences between predictions and measurements are also present in data ranges, which can be attributed to changes in inlet humidity, or in the fitted parameters.

[2] Values have been escalated due to confidentiality reasons

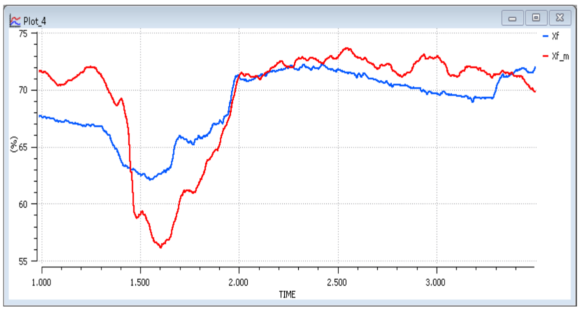

Figure 10: outlet fiber humidity $X_f{}^2$ vs time (s). (red - measurement, blue - model).

6 CONCLUSIONS

In this work, a modelling challenge for a medium density fiberboard dryer has been addressed to an acceptable level, for further use in a Model-Predictive Controller.

Due to the limited availability of process measurements, as well as the complexity of drying dynamics, a grey-box approach has been chosen. Parameters and unknown relationships between variables have been experimentally identified through data reconciliation, but this has been shown to not provide sufficiently accurate predictions. Therefore, moving horizon parameter estimation (MHE) will be required online to continuously adjust the model to actual operation. This is expected to increase significantly the consistency of the predictions. Moreover, it has also been shown that one of the sensors (that of the hot air pressure) provides untrustworthy information.

Future work planned for the project consists of the implementation of the online MHE and MPC. This controller will be first tested with the currently implemented model, analyzing its robustness against changes in the model representing possible regions of operation that are not well fitted.

Acknowledgements

This research is funded by the Spanish Government MINECO/FEDER DPI2015-70975-P.

References

[1] "European Panel Federation," [Online]. Available: europanels.org/products--producers/products/mdf.

[2] J. Andersson, J. Åkesson and M. Diehl, "CasADi -- A symbolic package for automatic differentiation and optimal control," in *Recent*

Advances in Algorithmic Differentiation, Springer, 2012, pp. 297-307.

[3] "EcosimPro. Dynamic Modeling & Simulation Tool," [Online]. Available: www.ecosimpro.com.

[4] S. Pang, "Mathematical Modelling of MDF Fibre Drying: Drying Optimisation," *Drying Technology,* vol. 18, no. 7, pp. 1433-1448, 2000.

[5] O. Melander and A. Rasmuson, "Mathematical Modeling of Heat, Mass, and Momentum Transport in MDF Fiber Drying," *Drying Technology,* vol. 29, no. 1, pp. 64-72, 2010.

[6] P. Tsilingris, "Thermophysical and transport properties of humid air at temperature range between 0 and 100◦C," *Energy Convers. Manag.,* vol. 49, no. 5, pp. 1098-1110, 2008.

[7] L. M., T. Edgar and L. Lasdon, "Efficient data reconciliation and estimation for dynamic processes using nonlinear programming techniques.," *Comput. Chem. Eng.,* vol. 16, no. 10-11, pp. 963-986, 1992.

[8] P. Huber, "Robust statistics," in *International Encyclopedia of Statistical Science*, M. Lovric, Ed., Springer Berlin, 2014, pp. 1248-1251.

[9] R. Čiegis and V. Starikovičius, "Mathematical modeling of wood drying process," *Mathematical Modelling and Analysis,* vol. 7, no. 2, pp. 177-190, 2002.

[10] R. Stull, "Wet-Bulb Temperature from Relative Humidity and Air Temperature," *Journal of Applied Meteorology and Climatology,* vol. 50, no. 11, pp. 2267-2269, 2011.