

Study of the multicylinder drying section of the Klabin-PR MP-7 paper machine

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ABSTRACT: Multicylinder sections of paper dryers consume the most energy in an industrial plant. They are also responsible for the final characteristics of the paper produced. In this context, the modeling of the paper drying process is very important, and is normally done by phenomenological approaches. An interesting and promising alternative, due to the possibilities of its application, is through the identification of an operational standard behavior, obtained by the use of neural networks in the simulation of the final paper moisture content. This alternative was implemented in the drying section of the Klabin Paraná Papeis S.A. (Klabin-PR) MP-7 paper machine. For this study, we collected operational data related directly and indirectly to the drying process, composing a database with 110 preselected variables. These data were analyzed with the help of Statistica Neural Network software, which, besides its use for training and choosing the more capable neural networks to model the chosen variable, allows the selection of the group of variables of larger influence in the studied process. The results obtained by the use of the neural network modeling were quite satisfactory, with an average error of less than 2% in the prediction of the final paper moisture content.

Application: Neural networks may be useful to help control moisture content and increase dryer efficiency.

Water removal is an essential stage in paper production. In this phase, the drying process can account for 2/3 of the energy requested for paper production (Wilhelmsson et al [1]). Many of paper's final characteristics depend on a good control of variables in the drying process.

In this context, modeling the drying process becomes quite important. Until now, models have been based on the analysis of phenomenological models that represent the physical industrial dryer as a whole.

An interesting and promising alternative procedure, is the identification of an operational standard behavior of the drying process, obtained by the use of neural networks in the simulation of the final paper moisture content. In this work, this alternative was put into practice in the multicylinder drying section of the Klabin Paraná Papeis S.A. (Klabin-PR) MP-7 paper machine. We studied the characteristics of industrial paper dryers similar to the Klabin-PR MP-7 paper machine. This study also helped point out the difficulties of conventional modeling, due to the complexity of the phenomena and the amount of involved variables.

On the other hand, variables that don't usually appear in phenomenological (conventional) modeling, such as those related to the stage of mass/pulp preparation (degree of refining, kappa number, chemical dosages, etc.), can be part of the database. As physical models that involve those variables are not found

in the literature, we thought it would be worthwhile to quantify their effects, with the aid of neural networks.

Klabin-PR MP-7 operational data were analyzed with the help of a neural network commercial software, which facilitated the computer simulation of changes in process variables and the evaluation of the results at the exit of the drying section. This also opened the future possibility of using neural networks in process control, in situations where the sensors are inoperative or being calibrated.

DRYING OF PAPER

General aspects

Paper drying presents characteristics in common with the other types of drying processes. The knowledge of the heat and mass transfer mechanisms becomes fundamental for the understanding of the drying process. These aspects motivated research more specifically related to the fundamental concepts associated to the paper/cellulose drying, as presented by Motta Lima [2].

Conventional drying of paper

Conventional drying of paper is accomplished in multicylinder sections of a paper machine. Polat and Mujumdar present an interesting description of these sections [3]. They describe iron cylinders, with 1.0 to 2.0 m of diameter, to almost 10 m of extension and approximately 2.5 cm thick. These are heated by the internal condensation of saturated vapor (up to 150 psi). The heat is transferred through

the wall of the cylinder to the paper film in contact with its external surface. This surface should be extremely flat, polished and free from imperfections, so that it does not leave marks or defects in the paper. The dryers can have 20 to 70 cylinders, depending upon the paper type to be processed and the specified velocity of the machine.

To analyze the heat transfer process inside the dryer, we can visualize it as a succession of resistances to the heat flow, from the saturated vapor to the drying air, going through the condensed water formed, the cylinder wall, the paper film, and the drying screen/felt. Figure 1 presents, schematically, the sequence of resistances to the heat flow. Among these, the contact resistance, the resistance of the drying screen/felt and, in particular, resistance to the paper film, can be considered among the more complex functions of the physical phenomena in the drying process in the analysis and modeling of this kind of process.

In the case of the Klabin-PR MP-7 paper machine, the industrial dryer is composed of 48 cylinders with diameters of 1826 mm, lengths of 6370 mm, and thicknesses of 76 mm, divided into five groups (batteries) of drying cylinders.

Historically, the paper film enters the MP-7 drying section with a moisture content of about 56% and leaves the last section with values between 5% to 9% (wet basis). The drying cylinders operate with pressures from 5.0 to 10.0 kgf/cm².

The higher pressures are applied in the last drying groups. The first groups takes advantage of part of the recovered vapor of the cylinders that operate with higher pressures, in a cascade system. The pressure differential between the vapor feed and the condensation collection line is in the range of 0.6 to 1.1 kgf/cm².

In Klabin-PR MP-7, as in most modern paper machines, the drying section is protected by a system of hoods. This allows for better control of inside air conditions and good removal of the humidity liberated by the paper. For that, hot air blowers and humidified air exhausters (to the atmosphere) are arranged along the course of the section.

Some other paper machine operating characteristics also affect the drying process:

- Drying screen/felt characteristics
- Admitted/blown air condition
- The amount of drag/carrying vapor (for condensed water removal)
- Siphon characteristics, etc.

Some of those parameters appear indirectly in the databases starting from related variables.

Modeling of conventional paper drying

Several reported models for multicylinder drying sections are available, all approaching the problem in a conventional way, by phenomenological modeling.

One of the first simulations (modeling) of the drying section of conventional paper dryers was accomplished by Nissan and his collaborators (Nissan and Kaye [4]; Nissan and Hansen [5]; Nissan and George [6]). Those works investigated heat transfer and water removal in multicylinder sections. They developed a theory to describe heat conduction in the paper material and experimental tests to verify the adaptation of the theory to the obtained results.

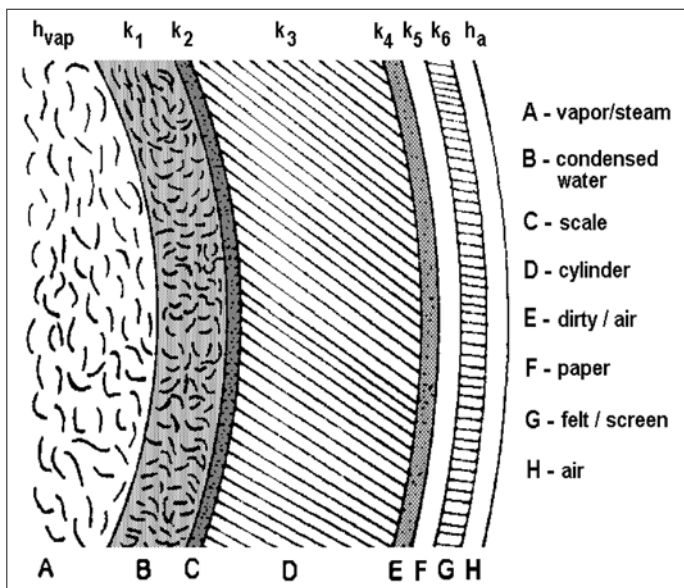
Other important references in this research field are the works of Videau and Lemaitre [7] and Wilhelmsson et al [8]. Those authors used some of the procedures developed by Nissan et al. These works demonstrate all the complexity involved with the classic (phenomenological) mathematical modeling.

Neural network application

The use of neural networks is justified for several reasons. In spite of the high level reached by classic modeling, the models are complex and present some empiric parameters. Neural networks allow the inclusion of difficultly modeled variables, they can be executed quickly, and they quickly adapt to process changes.

Two other factors justify the application of neural networks in this kind of work:

- Power—Neural networks are sophisticated modeling techniques, capable to model extremely complex functions, with high non linearity degree.
- Ease of use—Neural networks learn by examples. Starting from the collection of representative process operational data, the training algorithms automatically “learn” the structure of the data.



1. Heat transfer resistances (Polat and Mujumdar, 1987).

The availability of paper drying operational data in Klabin-PR favored the application of this technique.

For neural network training, the data should contain input examples with the corresponding outputs, which facilitates the neural network to learn the relationship between these two groups of data. The learning algorithms more commonly used work with the groups of input-output data in the adjustment of the weights factors of the connections among the neurons layers, in way to minimize the prediction deviations. If the network is trained properly, it means that it learned how to model the function that relates the input-output variables and that it can be used, subsequently, to predict outputs where or when they are not known.

In the paper and cellulose industry, we found some examples of the use of neural networks. Edwards et al [9] proposed their use to predict and control paper film surface deformation. Another interesting work, by Miyanishi and Shimada [10] used neural networks to diagnose paper films rupture in a press-paper machine.

In the field of paper drying, Huang and Mujumdar[11] used neural networks to predict the performance of an industrial Yankee dryer. According to the authors, this performance depends on very complex relations, frequently based in empiricism. The main difficulty is that there is not a satisfactory connection between the knowledge of drying mechanisms, which is microscopic by nature, and the dryer global operation, which is inherently macroscopic.

METHODOLOGY

Our study followed these steps:

1. Identification of variables that influence the drying process in the industrial paper dryer.
2. Acquisition of a significant database of industrial values synchronized with the final paper leaf/film moisture content.
3. Treatment of the database, removing spurious values or with high dispersion.

PROCESS SIMULATION

Characteristic	Standard	Unit
Bendtsen roughness	800	mL/min
Density	651	kg/m ³
L elongation	1.3	%
T elongation	4.00	%
Thickness	430.0	mm
Basis weight	266.0	g/m ²
L stiffness	422	mN.5cm
T stiffness	160	mN.5cm
L grip	20.0	kN/m
T grip	100	kN/m
Moisture content	6.5	%

I. KlaPak 26 card specifications.

4. Training and validation of neural networks to be able to predict the final paper leaf/film moisture content;
5. Removal of variables with low prediction power to obtain a subgroup of variables of larger influence in the process.
6. Training and validation of new, more compact neural networks able to predict the final paper leaf/film moisture content.

All the necessary data were directly collected from the Klabin-PR paper drying process, by means of industrial meters connected to the distributed control digital system (DCDS) of the MP-7 unit. At first, the choice of the variables that affect the drying process (more specifically, the final average moisture content) was based on paper drying literature, with the help of operation personnel and field specialists.

Three software programs were used for database preparing and analysis: one to collect and store the DCDS data; a second to refine the database; and a third to train and validate neural networks capable of learning the industrial data pattern of behavior in relation to the final paper leaf/film average moisture content.

Material characterization

Operational data were collected from the production of Klabin liquid board, KlaPak 26 (basis weight 266 g/m²), a duplex card used in packaging for an extensive range of food products, such as long-life milk, milk cremate, yogurt, tomato extract and pulp, mayonnaise, fruit juice, etc.

The KlaPak 26 card has high levels of rigidity and impression quality, plus high resistance to liquids absorption. It is composed of two layers of unbleached

Parameter	Unit
1. Paper machine velocity	m/min
2. Paper basis weight	g/m ²
3. Film/paper thickness	mm
4. Vapor feed pressure	kgf/cm ²
5. Vapor feed flow	ton/h
6. Pressure differential	kgf/cm ²
7. Condensed water return flow	ton/h
8. Admitted (blown) air temperature	°C
9. Vapor box pressure	kgf/cm ²
10. Pulp/mass conductivity	mS/cm ²
11. Pulp/mass kappa number	—
12. Consistence in the input/feed box	%
13. White water" consistence	%
14. Reject consume	ton/h
15. Vacuum level in the forming section	mca
16. Jet/screen velocity ratio	—
17. Cellulose pulp/mass	pH
18. Pulp/mass temperature	°C
19. Pulp/mass degree of refine	SR
20. Specific consume of chemicals	kg/ton
21. Final paper moisture content	%, dry basis

II. Parameters analyzed by the neural networks.

kraft cellulose (base and half layers), that represent, respectively, 24% and 52% of the paper total dry weight, and a covering layer of bleached kraft cellulose (24% remaining). The base and half layers are 100% long-fiber cellulose, obtained by kraft pulping of *Pinus taeda* wood (kappa number = 70). The superior (covering) layer is also obtained by the kraft pulping process, but from a mixture of 70% short-fiber cellulose (*Eucalyptus grandis* wood) and 30% long-fiber cellulose (*P. taeda* wood). For this layer, cellulose bleaching is made by a totally chlorine free (TCF) process, reaching a whiteness of 88 ISO. **Table I** presents the KlaPak 26 card specifications.

Data acquisition and treatment

The DCDS includes the mass/pulp preparation stage and the MP-7 paper machine as a whole, informing, by means of on-line sensors, the situation of relevant process variables.

An interconnection between the DCDS and the Pi-System (Plant Information, OSI Software, Inc.) software was used to facilitate the collection and initial analysis of the operational data. In this stage, the data were filtered so that

the events were only relative to the KlaPak 26 production.

We used the following criteria in developing the database:

- Choice of substages with continuous production of KlaPak 26 greater than 10 days
- Elimination of variables whose measure elements (instruments) came back more than 15% of bad data
- Elimination of values which were three standard deviations above the average
- Narrowing the paper moisture content to 5.5% to 7.5%, independent of the standard deviation.

Analyzed variables

The variables presented here sometimes represent groups of variables. **Table II** lists the parameters used in analyzing the initial database.

Paper moisture content exiting the drying section is the variable to be estimated (dependent variable), being used in the comparison and adjustment of the weights attributed to the neural network connections.

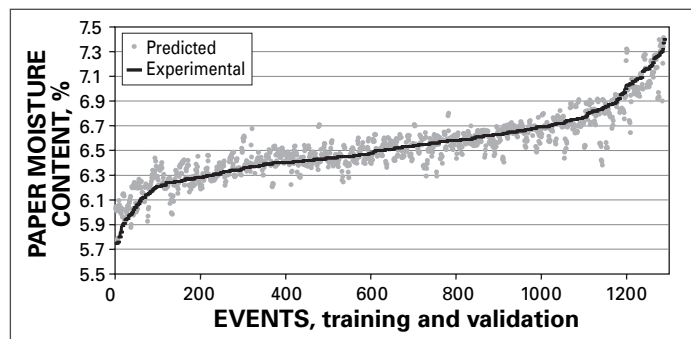
Neural network training and selection

After treating the collected MP-7 operational data, the information was exported to the Statistica Neural Network 4.0 (Statsoft, Inc.) software to look for the better neural network configuration.

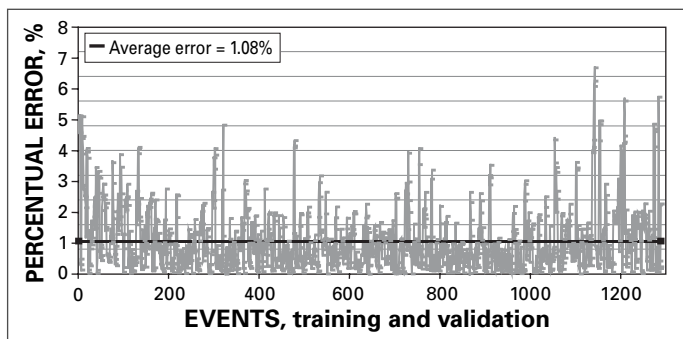
The selection of the neural networks started with the complete database. It ended with the development of a network that uses the smallest number of parameters to satisfactorily represent the final paper moisture content.

We established some criteria for training and selection of the neural networks. The database was divided into one subgroup for training and into another for verification (validation), maintaining a relationship of 70% and 30%, respectively. After the training period, we intended to present a data set never seen by the network before, to avoid over-training the network.

The proper search for the neural network that best represents the operational database pattern of behavior in relation to the final paper leaf/film average moisture content is done by changing the network type (radial base or multi-layer feed-forward networks), number of layers, number of neurons in the



2. Experimental and predicted (neural network) average moisture content (dry basis).



3. Percent error: experimental and predicted (neural network) average moisture content.

internal layer, training algorithms, activation functions, normalization functions, and amount of input variables (choice of major subgroups).

RESULTS AND DISCUSSION

Figure 2 shows a comparative analysis among the observed/measured (experimental) values and the predicted (neural network) values for the paper moisture content (% dry basis). These results were obtained for a 1289 events database; moisture content values ranged from 5.75% to 7.40% (data was classified in growing order of moisture content).

The stated moisture content interval represents the real operation of the MP-7 paper machine. As observed in Fig. 2, there is a larger concentration of data in the region from 6.20% to 6.90%, representing 85% of the events.

The neural network that best represented these data presented the following configuration: 15:15:7:1:1 multi-layer perceptrons (MLP), i.e., 15 input variables, all normalized, seven neurons in the internal layer, one output variable, and the final average moisture content.

Table III lists the input variables for this neural network configuration in decreasing order of importance (weight attributed by the network to each variable).

Figure 3 presents the behavior of the percent error/deviation related to Fig. 2 ($[\text{observed} - \text{predicted}]/\text{observed}$). The average error in the central area was 0.96%, versus 1.65% in the areas to the right and left of that interval. The largest density of events in the central area justifies this fact. The prediction general average error was 1.08%, with maximum values reaching 6.9%. This can be considered a satisfactory result.

Figure 2 presents one of the results we obtained. Other analyses were made for similar behaviors, but with different characteristics, as, for example, the training algorithm, the amount of neurons in the internal layer, or the subgroup of chosen variables. For example, we applied the originally adjusted neural network to 100 events collected from process data 15 days outside of the training period. The average error increased to 2.55%. For the same database, using 25 input variables and a better-configured neural network for this case, the average error was 0.95%.

CONCLUSIONS

Results were significantly close to the observed MP-7 paper machine behavior, with an average error/deviation of 1.08%. This adjustment is adequate for the use of the neural network in the forecast and simulation of changes in paper machine operation. It also helps us to quantify the effects of the variables involved.

An important part of this work is related to the identification of the variables sub-groups, which are more relevant for predicting final paper average moisture content.

Neural network application for events distant from the training period is less reliable, because the prediction power decreased. This demonstrates the need to continuously train the process.

The reduction of the number of input variables establishes a commitment between the prediction error and the complexity of the model. As presented, the reduction of 25 to 15 variables increased the error in nonsignificant levels for justifying the presence of more than 10 variables in the model.

Variables	Unit
1. Total basis weight	g/m ²
2. Vapor feed pressure	kgf/cm ²
3. Vapor feed pressure	ton/h
4. Machine velocity	m/min
5. Condensed water return flow	ton/h
6. Film/paper thickness	mm
7. Pressure differential	kgf/cm ²
8. Admitted (blown) air temperature	°C
9. Pulp/mass degree of refine	SR
10. Half layer basis weight	g/m ²
11. Vapor box pressure	kgf/cm ²
12. Pulp/mass temperature	°C
13. Superior dewatering vacuum	bar
14. Half layer pulp/mass	pH
15. Vacuum in the forming section	bar

III. Input variables classification.

Some of the variables that appear in phenomenological models are represented in the final subgroup of variables selected by the neural network (Table II) that reinforce the quality of the obtained result. **TJ**

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INSIGHTS FROM THE AUTHORS

We chose this topic to research because of its importance to KLABIN-PR. It complements previous research on the application of neural networks in the analysis of paper machines.

The most difficult aspect of this research was the data collection. Fortunately KLABIN-PR was able to facilitate the acquisition and data evaluation.

The applicability and neural networks potential for paper machine's simulation and process control was the most surprising finding of this work. We feel that neural networks are certainly a useful and attractive alternative for paper machines simulation and process control.

The next step in this research will be to apply neural network analysis to other paper properties and paper machine variables.

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