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Towards multivariate statistical process control in the wood pellet industry

Torbjörn A. Lestander [a,*], Conny Holmberg [b], Lars Stenberg [b], Roger Lehtonen [b]

[a] Swedish University of Agricultural Sciences, Unit of Biomass Technology and Chemistry, SE – 901 83 Umeå, Sweden
[b] Bioenergi i Luleå AB, P.O. Box 50100, SE – 973 23 Luleå, Sweden

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ABSTRACT

Multivariate statistical process control (MSPC) based on principal component analysis (PCA) and partial least squares (PLS) regression was simulated, based on industrial data collected over a two-year period within a plant producing wood pellets as biofuel. The data used in the simulations consisted of values of five variables of analysed intermediate products (sawdust and powder) and end products (pellets), acquired during processes with seven on-line settings of controls.

PCA global modelling revealed an overlap in the data between years and detected three different pellet types. Correlations within the dataset indicated there was a time lag of up to 14 h. Therefore, PLS prediction of current product values was based on observations containing the current process settings and all variable values within a preceding 18 h time interval. Global models showed that predictions of the dryness of sawdust, milled sawdust and pellets had good accuracy, whereas predictions of pellet bulk density and mechanical durability were less accurate. Dynamic and local PLS modelling showed that more accurate predictions of pellet dryness were obtained if all previous observations were included in the calibration set rather than observations in calibration windows of the 10 or 100 preceding observations.

The results illustrate the possibilities to implement MSPC in the wood pellet industry, potentially handling huge amounts of data. To develop and implement the next phase of process control more parameters must be included in the MSPC models, e.g. data acquired using on-line instruments to continuously collect information on variations in the stream of material.

1. Introduction

A major objective for industrial activities in which biomaterials of varying quality are processed is to reduce the variability of the final products, using appropriate control systems, and thus ensure that they meet desired quality criteria. For this purpose, trend curves based on process parameters are of great potential value, and the vast majority of industrial plants use traditional statistical process control (SPC) [1] to continuously monitor process streams and adjust process settings accordingly. SPC is designed to maintain process quantities and quality by using statistical methods based on univariate process data [1,2]. The underlying goals are to maintain steady states (within statistically acceptable limits) and to detect faults at early stages.

SPC becomes more complex when more monitoring variables are added to control smaller variations in the process, potentially leading to information overload for the process operators. Multivariate statistical process control (MSPC) [3,4] can overcome this problem. In MSPC multivariate data

* *Corresponding author*. Tel.: +46 90 786 87 95.
E-mail addresses: torbjorn.lestander@slu.se (T.A. Lestander), conny.holmberg@luleaenergi.se (C. Holmberg), lars.stenberg@bioenergilulea.se (L. Stenberg), roger.lehtonen@licabconsulting.se (R. Lehtonen).
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analysis techniques are used to compress the number of variables into a few components and to present the observations in a few plots with confidence regions. This provides possibilities to include large numbers of variables in the supervision system and still maintain a global overview of huge process datasets [5].

Many factories that could be regarded as kinds of biorefineries using materials and other resources (e.g. energy inputs) supplied by other plants within industrial biocombines, and thus have to adapt flexibly to meet changes in the outputs (or product requirements) of other closely linked plants. Interesting cases of such production systems are plants in the wood pellet industry, which produce a wood composite as a standardized biofuel [6] by pressing dried wood powder (e.g. milled sawdust) into pellets. In addition to supply and demand fluctuations, such plants are heavily influenced by variations in the quality of the raw material and sometimes dependent on surplus heat supplied by neighbouring plants.

The aims of this study were: to simulate MSPC, using principal component analysis and partial least squares regression, based on wood pellet production process data; to characterize variations in the monitored variables over time; to predict pellet dryness (which reflects the energy content of the biofuel produced); and, finally, to determine the potential of using MSPC for monitoring and predictions in the wood pellet industry.

2. Experimental

The wood pellet production process started with sawdust that was dried by heated gases (Fig. 1). The dried sawdust was milled into wood powder and pellets were formed from the powder in pellet presses. After cooling the pellets were stored and shipped to the customer and used as biofuel. Data on 12 available process parameters used in this study were collected every 2nd hour for two consecutive years with interruptions for malfunctions and yearly service and maintenance in summer time. The actual pellet plant was situated in Luleå, Sweden (65°35′N, 22°10′E) and was designed to produce 105,000 tons of wood pellets (8 mm in diameter) per year. This plant used surplus heat from an adjacent plant. The sawdust feedstock came from regional sawmills mainly sowing logs of Scots pine (*Pinus sylvestris* L.) and smaller quantities (<10%) of Norway spruce (*Picea abies* Karst. (L.)). During the studied two-year period experiments to produce fuel pellets from *Sphagnum ssp*. peat were done.

2.1. Sensors

The following on-line parameters were recorded when samples of dried sawdust, wood powder and pellets were collected:

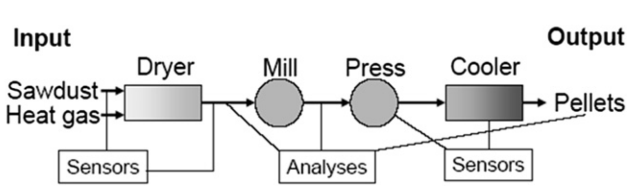

Fig. 1 – Simplified diagram of the studied wood pellet production process.

- plug flow, the input of raw material used in the process (here: 1 Hz ≈ 1 Mg h^{-1} sawdust);
- gas flow, the volume of heated gas entering the plant (m^3 h^{-1});
- MWh, the energy content (MWh) in the drying gas;
- CBdry, the temperature of drying gas entering the dryer (°C);
- CAdry, the temperature of the gas leaving the dryer (°C);
- press, the number of pellet presses in use;
- Ccool, the temperature of air leaving the pellet cooler (°C).

2.2. Analyses

The following off-line parameters were analysed:

- sawdust, the dry substance content (%, based on wet weight) of the sawdust;
- powder, the dry substance content (%) of the milled (<3.5 mm) sawdust (wood powder);
- pellet, the dry substance content (%) of the pellets;
- pelletvw, the weight of 1 L of the pellets (g L^{-1});
- fines, the percentage (%) of fines in the pellet fraction, defined as the percentage, by weight, of the material that passed through a 2 mm sieve when tumbling pellets in a Borregaard LTII apparatus [7] for 30 s.

The dry substance contents of dried sawdust particles (<4 mm wide), powder (dried and milled sawdust) and pellets were determined by analysing subsamples of *c.* 5 g using a moisture analyser [8] equipped with an infrared drying device.

2.3. Data analysis

Models based on time series of data can be constructed with various time scales using multivariate techniques, such as principal component analysis (PCA) [9] or partial least squares (PLS) regression [10]. This can be very useful for exploring phenomena such as memory effects or between-batch variations, after sectioning the data into appropriate time blocks [11].

Multivariate models for the MSPC simulations constructed in this study were based on a mathematical matrix consisting of on-line and off-line data for the 12 variables as columns and 6055 observations ordered in time as rows. Further, time blocks were constructed by adding $n \times 12$ columns to each observation with variable data from n preceding observations. Pellet dryness was then predicted, as a reference variable, by dynamic PLS modelling using different calibration windows, constituting the calibration sets to model pellet dryness and to predict the next value of this property. Two fixed sizes of 10 (C10) or 100 (C100) preceding observations (rows) together with current on-line settings were used as moving windows to obtain calibration sets in order to predict the next (current) value of pellet dryness. The model, named CACC, was based on a window that accumulated one observation as the successive prediction continued.

Global PLS modelling of the same time blocks was used to predict not only pellet dryness, but also properties of intermediate products and pellet quality. The three local models C10, C100 and CACC were compared to the global model for pellet dryness.