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Simulating Moisture Content and Flow of Sawdust in a Storage Silo with Cellular Automata

Abstract: In the field of modelling, it is commonplace to model only the expected value of the target variable. However, the uncertainty, or the variance related to this output variable is rarely discussed. This study provides a suggestion to estimate the expected value and uncertainty of the silo output moisture of a granular material in a storage system using a Cellular Automata model. In addition, a Fourier function –based trend analysis is carried out to estimate the storage delay. The study also discusses the implementation and computational details of the model.

Keywords: Granular Material, Moisture Migration, Dynamic Model, Storage Behavior

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1 Background & Aims

Biomass is expected to have a significant role in sustainable fuel production and replacing fossil energy sources Sawdust is an important raw material for biorefineries and energy production (Chaula et al. 2014; Casau et al. 2022) The moisture content of the sawdust has a relatively large effect on the energy efficiency (Chaula et al. 2014) and moreover on the environmental impact of the process. An accurate estimate of the moisture content and its reliability is of great importance to achieve a good controllability of these processes and always ensure energy-efficient production. The moisture content can be measured directly from the sawdust (Stasiak et al. 2014). However, for example in large storage systems these physical measurements often demand extensive design and maintenance efforts, and thus might appear impractical and unsuitable for on-line use. One approach to overcome the problem with localized measurements is to use wireless sensors providing the moisture content distribution information of a granular material in continuous manner (Jian et al. 2009). A soft sensor-based monitoring of the moisture content seems attractive, as it would allow to evaluate the transient inner state of the storage system at least qualitatively and to quantitatively estimate the storage system output. For this aim, a Cellular Automation (CA) based simulation model that could be applied to estimate simultaneously propagation of moisture content and granular material movement inside the silo with respect to time is proposed.

2 Material & Methods

CA is a modelling technique, in which usually complex real-world systems of which models demand extensive mathematical descriptions are simplified to a defined ruleset. In the model, each of the cells presents a modelling entity that has a set of properties and neighbor cells. A characteristic property of a CA model is its rule based stochastic interaction of a cell with its neighbors, resulting as a semi–random behavior. Typically, the granular material flow is described as individual particles, which obviously in the case of tons of sawdust requires a description extensively dense computational grid. In practical applications, such grid is usually not applicable in real-time simulations. In this study, the storage silo is simulated as a *h x w* sized grid, in which each of the cell presents a sawdust mass unit, of which properties are mass (*m*) and moisture content (*y*). Overall, each of the sawdust cells is treated as a unit volume or as a mass unit. In this way, the computational grid size can be significantly reduced that results as a reduced time complexity. However, because of this, the accuracy of the computations is compromised. In the end, the application area of the model sets the limits for the grid parameters.

2.1. Input data generation

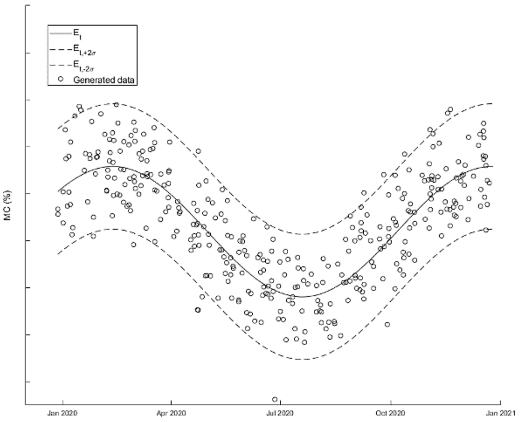

Figure 1. *Generated batch data for moisture content.*

The simulation study is carried out as a Monte Carlo approach. In the simulation, the monthly variation of the moisture of the delivered sawdust batches is estimated to follow a time–variant normal distribution, in which the expected value of the distribution is estimated using a Fourier function of a form

$$E_t(\theta, a, t) = \theta_0 + \theta_1 \cos(a\pi t) + \theta_2 \sin(a\pi t)\,. \qquad (1)$$

The standard deviation of the distribution is kept constant in this simulation, as it is assumed that of the variance in the input moisture is mainly composed of the analysis and sampling error. An exemplified generated data set for a one year–long simulation presenting the sawdust batches with mass *m* and moisture *y* is provided in Figure 1.

2.2. Condensed Rule Sets for Storage Behavior

As a general CA system, the silo behavior is defined based on four rule sets, which include the following categories

1. Overall mass–balance of the silo
2. Behavior of the screw feeder at the bottom of the silo
3. Particle or mass movement between cells
4. Moisture migration between the cells

The more specific set of rules define the overall behavior. The overall mass balance of the silo is here considered as a simple mass in mass out system, in which the m_{in} is defined as the arriving sawdust batches from the delivery site and the m_{out} reflects the behavior of the screw feeder located on the bottom of the silo. The defined input mass flow, m_{in} is a pulse–like flow simulating the filling of the silo, whereas m_{out} is the output flow. To define the output flow, the impact area and use of the screw feeder needs to be considered. In this study, the geometry is simplified as a rectangle with a size of h_s x l_s. In other words, the screw feeder impact area is of size *A* and constitutes of N_{out} individual cells. The output moisture is a randomly weighted average of the moisture in each cell corresponding to the screw feeder cells. The uncertainty of the output moisture can be treated in different ways, but in this work the moisture range is given as the 10th and 90th percentiles of the moisture contents in the lower section of the silo.

The particles in the silo are allowed to transfer from one cell to another because of the gravity (vertical component) and because of the particle collision interactions (horizontal component). Both phenomena are defined to occur with a certain probability and in a pre–defined neighborhood. In the work of previous authors, each discrete particle has a flow velocity that is affected by gravity and interactions of neighboring particles. As pointed out in previous sections, this demands a dense computational grid, so in this work the potential of the particles to transfer from one cell to another is approximated by using an average *mass loss* in the cell. This means that the mass is allowed to transfer from one cell to another, if there is a porous space available. The moisture is allowed to migrate from one cell to another because of mass–transfer potential, namely concentration difference. The mass–transfer approach has been previously verified to correspond well to CFD simulations. (Chopard & Droz 1991) The selection of the interacting cell is carried out using roulette-wheel selection in all cases.

3 Results & Discussion

First, the modeling approach was successfully validated for the wheat storage data presented in (Jian et al. 2009). Then, the moisture content of the simulated data was estimated. The output moisture with corresponding uncertainty limits is presented in Figure 2. The uncertainty range is taken here as the 10th and 90th quantiles in a silo subsample. Furthermore, using a model–based estimation approach, the storage delay, ergo the delay between the loading and the unloading of the material, can be by formulating a maximum likelihood estimation problem with respect to storage delay (τ).

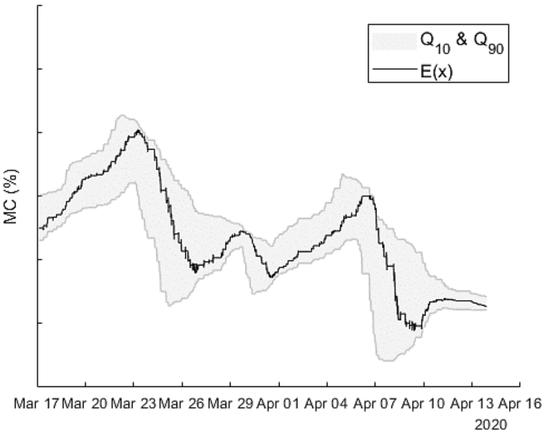

Figure 2. *The simulated silo output moisture in a month–long simulation with corresponding confidence interval given here as* Q_{10} and Q_{90} *of the moisture distribution of a subsample in a pre–defined silo section.*

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