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DIGITAL TWINS WITH EMBEDDED PARTICLE SIMULATION

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Transport and processing of granular media is of the essence in the mining and construction industries. The activities are large consumers of energy, raw material, and involves expensive infrastructure and equipment. Optimization is therefore a continuous ongoing activity but associated with many difficulties. One complicating factor is the natural variations in properties of the raw material that enters the process. These variations propagate through the chain of processes in a complicated way, adding to the process dynamics. The performance of each individual sub-process is a function of the (not fully known) material state and of the process control. Each sub-process alters the state of the material. Even the transport and storage processes may affect the material in a significant way, e.g., mixing, packing or segregation. This complex interaction between sub-processes and materials makes modelling and optimization of the complex chain of processes very difficult [1]. In fact, many times there is not sufficient data for constructing models of the full process dynamics or for studying the cause and effect behind variations. The equipment is well-instrumented, and the process control systems produce large volumes of data. The problem is that there are few direct measurements of the properties of the granular material and its motion. Sensors can only be mounted in certain places and the material is rather opaque to the forms of radiation that reveal their properties. Therefore, most observations are indirect or consist of measurements on the surface, which constitutes only a small fraction of the bulk of the material. This creates blind spots in observing the state of the material and in tracking its movements along the chain of processes, see Fig. 1.

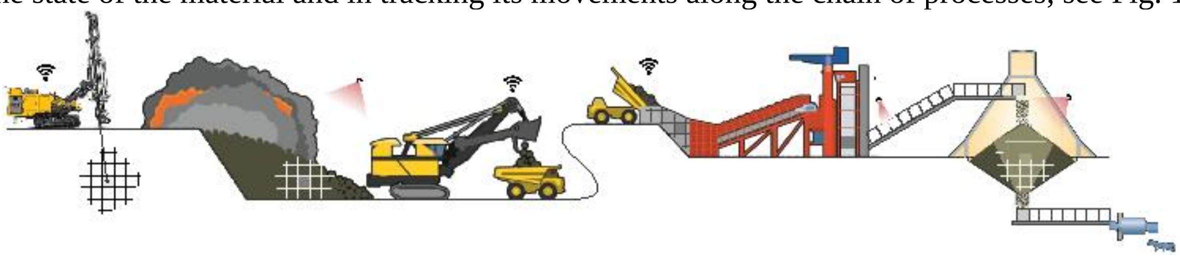

Figure 1. *Illustration of material tracking through the chain of processes in an open pit mine.*

To remedy this, we explore material-oriented digital twins of systems doing transport and processing of granular media with embedded particle simulation. The idea is to represent the material and its movements in a structured data format based on a particle representation. In addition to the material's identity and current position, the particle data structure supports the reading and writing of observations from sensors and equipment along the chain of processes. When connected equipment performs unit operations on the material, the digital copy is updated accordingly. When the material reaches blind spots in the system, for example, a silo or a stockpile, the material updates are driven by simulation models that are fed with data from the control system and available sensors in real-time.

For the sake of computational performance and memory, the particles are pseudo-particles that represents a large collection of real particles of mineral ore with a distribution of size and shape. To guarantee real-time performance of the particle dynamics, we combine physics-based simulation with data-driven model order reduction. The latter is trained off-line in advance with the physics-based model, which is a nonsmooth discrete element method [2], and using authentic CAD models and control signals for the in- and outflow. The reduced order model [3] predicts the flow fields that occur in a pile or silo as a function of the material distribution and discharge rate. Inflowing material is simulated with the physics-based model until it lands and come to rest on the surface of the pile. After that, the reduced model takes over the transport of the particles by advection with the predicted velocity field. The combination of the two models in an executable application that can be embedded in a digital twin architecture, we call a *granular surrogate*. With this solution it is possible to predict the identity and properties of the material that exit the pile or silo in relation to what enters. It can also be used for computing and visualizing the properties of the material and how these are spatially distributed in the storage unit. This is demonstrated in Fig. 2.

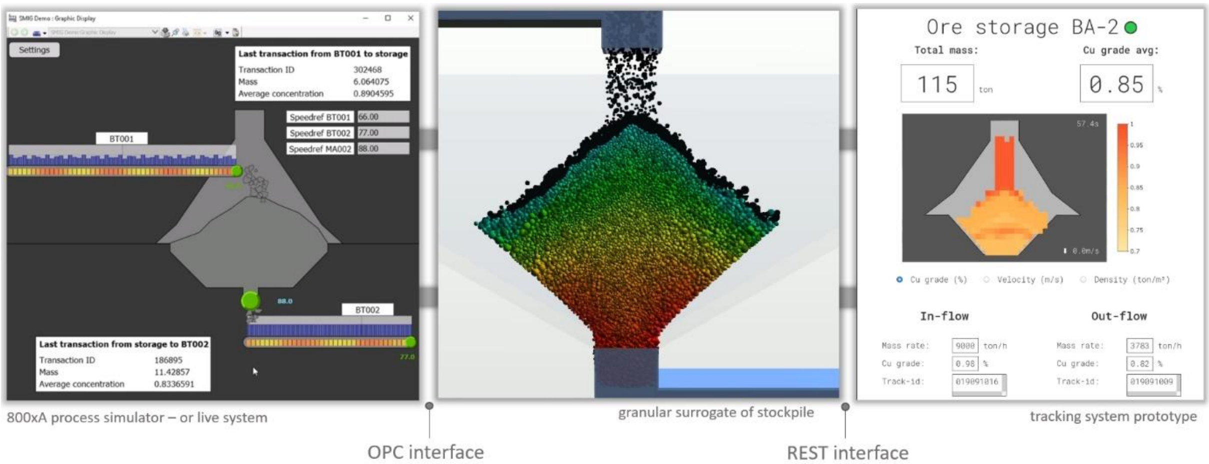

Figure 2. *Demonstration of a granular surrogate for a stockpile (centre) coupled to the process control system (left) and visual presentation of the material properties currently inside the pile (right). Particle tracking id:s are interchanged with the control system for material on the in-coming and out-going conveyors.*

A fully simulated demonstrator system of a mine-to-mill process, as in Fig. 1, is created and used for producing synthetic data, including variations in throughput and power draw of the crusher and grinding circuit varies due to variations in the ore properties. Examples of statistical analysis enabled by the material tracking system is provided.

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