

Behavioural model of a bulk material hopper for virtual commissioning

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Abstract. This paper presents the design, implementation, and experimental validation of a behavioural model of a bulk material process hopper for virtual commissioning at the machine level. The mathematical model is based on the geometry of a truncated pyramid-shaped hopper and Bernoulli's equation for mass flow rate calculation. It was implemented in the SIMIT environment and integrated with TIA Portal. Validation using a physical hopper model at SKARTEK s.r.o. achieved an average correlation of 0.977 between mass response curves. The model enables the development of control algorithms without physical prototypes, in line with Industry 4.0 principles.

Keywords. behavioural model, bulk material hopper, virtual commissioning, SIMIT, TIA Portal

1 Introduction

Nowadays, the development of virtual models is becoming increasingly widespread in industry with the aim of improving the efficiency, flexibility, and quality of manufacturing systems. One of the key areas is virtual commissioning, which enables the simulation and testing of production equipment prior to its physical implementation, thereby significantly reducing commissioning time and minimizing the risk of errors in the real system (Tjahjono et al., 2017). Bulk material hoppers constitute an integral part of automated production processes in the construction, food processing, chemical, and agricultural industries.

A current trend in industry is the increase of production capacity while simultaneously reducing the time required for the design and commissioning of production lines. This leads to a higher risk of errors during the design, implementation, and debugging of systems, resulting in production delays and increased costs. Identifying and eliminating an error already during the initial design phase is more economically advantageous than resolving it during the physical

implementation stage. For these reasons, simulation tools are being developed to eliminate as many deficiencies as possible before the physical implementation of the system (Kopček et al., 2022).

To address these challenges and systematically evaluate the proposed approach, this paper formulates two key research questions (RQs) that guide the theoretical derivation, implementation, and experimental validation:

RQ1: How accurately can a SIMIT-based behavioral model reproduce the transient discharge dynamics (mass flow rate and weight profile over time) of a truncated pyramid-shaped bulk material hopper under real-time PLC control?

RQ2: To what extent does native integration between the SIMIT simulation platform and TIA Portal facilitate machine-level virtual commissioning in terms of signal mapping, execution synchronization, and model reusability compared to non-native simulation environments?

The aim of the presented work was to design and implement a behavioural model of a truncated pyramid-shaped process hopper in the SIMIT environment and to verify its validity through experimental comparison with a physical model built at SKARTEK s.r.o. The model is intended to serve as a digital twin for the development of PLC control algorithms, thereby eliminating the need for repeated construction of physical prototypes for different hopper variants (Pikna, 2025).

2 Theoretical background

2.1 Industry 4.0 and digital twin

The term Industry 4.0 refers to the fourth industrial revolution enabled by the introduction of the Internet of Things (IoT) into manufacturing environments. The vision of Industry 4.0 emphasizes global networks of machines within a smart factory environment, capable of autonomous information exchange and control of

their own production operations (Lechler et al., 2019; Tjahjono et al., 2017). Since collaboration among suppliers, manufacturers, and customers is essential for the transparency of the entire value chain, it is necessary to analyze the impact of Industry 4.0 on the supply chain as a whole.

To establish the theoretical basis for answering **RQ1**, it is essential to examine how digital twin architectures support virtual commissioning (VC). A digital twin could be defined as a virtual representation of a physical object, process, or system that enables its simulation, analysis, and optimization in real time (Kopček et al., 2022; Schroeder et al., 2016). In industrial automation, VC utilizes this twin to validate programmable logic controller (PLC) code prior to the physical installation of equipment, shifting software debugging from the shop floor to the virtual sandbox (Reinhart & Wünsch, 2007). This model-in-the-loop (MiL) and software-in-the-loop (SiL) paradigm drastically reduces project implementation risks, prevents mechanical collisions, and shortens deployment cycles (Hoffmann et al., 2021).

The commissioning process of an automation system involves several consecutive phases: preparation and installation of hardware and software, functional testing, correction and tuning, personnel training, transition to real operation, and subsequent support and maintenance (Barth & Fay, 2013). Thanks to behavioral simulation tools, most of these phases can be carried out virtually before physical deployment, which significantly reduces project risks and costs (Pikna, 2025). In the context of bulk material handling, behavioral models must accurately capture continuous mass flow rates and discrete actuator dynamics to serve as reliable validation targets for control logic (Klüber & Stark, 2020).

2.2 Simulation platform - SIMIT

Addressing **RQ2** requires a comparative evaluation of available simulation platforms regarding their capability to interface with industrial control hardware. Currently, several software platforms are used for creating behavioural models of industrial equipment, including MATLAB/Simulink, FlexSim, Factory I/O, and SIMUL8. Table 1 summarizes the main characteristics, primary applications, advantages, and limitations of these platforms.

Table 1. Comparison of prominent industrial simulation platforms for virtual commissioning

Platform	Main focus	Key characteristic
MATLAB / Simulink	Mathematical and control modelling	High analytical accuracy and extensive modelling capabilities

FlexSim	Manufacturing and logistics simulation	Advanced 3D visualization and process optimization
Factory I/O	Automation education and training	Fast creation of virtual automation scenarios
SIMUL8	Discrete-event simulation	Statistical analysis of process performance
SIMIT	Virtual commissioning	Native integration with Siemens automation systems

For the purposes of this work, SIMIT from Siemens was selected due to its native, shared-memory integration with SIMATIC systems and TIA Portal (Siemens AG, 2024). Unlike general-purpose tools like MATLAB/Simulink or discrete-event simulators like SIMUL8 that rely on intermediate OPC UA wrappers—which introduce communication latencies and tag configuration overhead—SIMIT operates as a synchronized behavioral extension of the virtual controller (PLCSIM Advanced / S7-1200).

SIMIT supports real-time process simulation and allows direct control via SIMATIC S7 PLCs through standard communication interfaces such as PROFINET, Modbus, and PROFIBUS (Siemens AG, 2024). Its modular block architecture enables seamless implementation of hydraulic, pneumatic, and mass-balance equations while supporting external C++ or MATLAB/Simulink co-simulations if required. This native integration directly satisfies the requirements of **RQ2** by ensuring deterministic execution synchronization and streamlined signal mapping.

3 Mathematical model of the hopper

3.1 Hopper geometry

The analyzed hopper is shaped as a **square pyramidal frustum** with unequal top and bottom bases (Pikna, 2025). The areas of the top base S_{top} and the bottom base S_{bot} are calculated according to the following equations (eq. 1, eq. 2):

$$S_{top} = a \times b \quad (1)$$

$$S_{bot} = m \times n \quad (2)$$

Where a , b are the sides of the top base, and m and n are the sides of the bottom base. The total volume of the hopper is calculated according to the formula (eq. 3) for the volume of a frustum of a pyramid:

$$V = \frac{H}{3} \times (S_{bot} + \sqrt{S_{bot} \times S_{top}} + S_{top}) \quad (3)$$

where H represents the maximum fill level of the material in the hopper.

In the physical model, the bottom base is identical to the discharge gate, while the model considers both dimensions separately for greater versatility.

3.2 Mass flow rate

The basis for calculating the material mass flow rate during discharge is Bernoulli's equation (eq. 4), which expresses the conservation of energy for a flowing fluid:

$$p + \frac{1}{2} \times \rho \times v^2 + \rho \times g \times h = \text{const.} \quad (4)$$

where p is the pressure [Pa], ρ is the density of the material in the vessel [kg/m^3], v is the flow velocity [m/s], g is the acceleration due to gravity [m/s^2], and h is the level height [m].

Using mathematical derivations, we express the equation for the flow rate through the gate (eq. 5). The area of the gate is expressed as follows:

$$S_{\text{gate}} = x \times y \quad (5)$$

where x and y are the maximum dimensions of the gate. By combining eq. 4 and eq. 5, the mathematical expression for the flow rate Q_v can be derived (eq. 6):

$$Q_v = S_{\text{gate}} \times \sqrt{2 \times g \times h} \quad (6)$$

Finally, the mass flow rate $\dot{m}$ is calculated (eq. 7) as follows:

$$\dot{m} = Q_v \times \rho \quad (7)$$

These equations form the computational core of the behavioural model and are implemented within its logical section in the SIMIT environment using standard mathematical blocks.

4 Physical model of the hopper

4.1 Physical model description

SKARTEK s.r.o. has developed a physical model (Fig. 1) of a process hopper as a scaled-down and simplified version of a real-world concrete bucket. This physical model is used to develop and verify control algorithms prior to their deployment on actual industrial equipment. Its main functional units consist of a pneumatic gate actuator, a sensor system, and a PLC control system. (Pikna, 2025)

4.2 Pneumatic actuator

The opening and closing of the discharge gate are performed by a FESTO pneumatic cylinder, type

ADN-25-130-A-PPS-A (536350). It is controlled by a FESTO solenoid valve, type VUVG-L10-P53C-T-M5-1P3, which is operated by a digital output of a Siemens S7-1200 PLC. The electrical and pneumatic schematics of the physical model were designed and functionally verified using the Festo FluidSim software.

4.3 Sensors

Three SICK sensors are used to monitor the pneumatic cylinder's position: two digital limit sensors for the end positions (home position HP and working position WP), which send a binary signal to the PLC, and one analog continuous position sensor. The weight of the hopper, including its contents, is measured by an EMSYST EMS 100-5kN strain gauge load cell. The control program implements a TARE function, which subtracts the weight of the empty hopper and displays the net weight of the filled material.

4.4 Control system

A Siemens S7-1200 PLC (type 1214C), programmed in the TIA Portal environment, was selected to control the entire process. The program includes the valve control logic, sensor signal processing, material weight calculation, and a Trace function designed for real-time recording of monitored variables with the option to export to CSV format. The same TIA Portal project was also utilized to interface with the behavioural model in SIMIT.



Figure 1. Physical model of the hopper

5 Behavioural model implementation (SIMIT)

5.1 Model architecture

The behavioural model of the hopper is divided into two functional sections: the visual section (Frontend) and the logical section (Backend). This architectural separation ensures model clarity, allows for independent modifications, and facilitates reuse by different users without requiring deep knowledge of the internal logic. The connection between SIMIT and TIA Portal is established through a standard communication interface, with both systems operating using shared PLC variables.

5.2 Frontend

The **Frontend** contains a graphical representation of the hopper and all control elements linked to TIA Portal. Here, the user configures the geometric dimensions of the hopper (top and bottom base sides, height, and gate dimensions) and the material density through editable input fields. The following control elements are available:

- **RESET** – Virtual filling of the hopper to maximum capacity (calculates the missing weight and adds it to the current value).
- **btnOpen / btnClose** – Manual opening and closing of the gate in MAN mode.
- **Slider** – Adjusting the gate opening percentage from 0 to 100% in manual mode.
- **Mode selector switch MAN/AUTO** – toggles between manual and automated control modes.

In automatic mode (AUTO), the user enters the target batch weight and the gate opening percentage. Upon pressing btnOpen, the gate opens and automatically closes once the target weight is reached. The current filling level of the hopper is continuously displayed via a bar graph and a numerical value in kilograms. Data for validation were collected exclusively in automated mode, thereby eliminating human error associated with manually closing the gate at the correct moment.

5.3 Backend

The Backend performs all mathematical model calculations in real-time. The computational chain consists of the following steps:

1. Calculation of the top and bottom base areas according to the specified dimensions.
2. Calculation of the maximum hopper volume.
3. Calculation of the current gate area as a function of the opening percentage.
4. Calculation of the volumetric and mass flow rates.
5. Continuous update of the material level (height) and weight within the hopper.

All operations are implemented using standard SIMIT blocks: sum, product, quotient, and the SQRT (square root) block. The logic incorporates a ramp block for gradual gate opening, ensuring that the gate does not open instantaneously upon pressing btnOpen. Instead, it opens progressively, aligning with the finite speed of the physical pneumatic actuator.

6 Data collection and experiments

Data collection from both the physical and behavioural models was conducted in TIA Portal using the Trace function. This feature allows for the selection of monitored variables, real-time visualization of their trends, and the export of measured data into a CSV format suitable for further analysis. Two key variables were monitored for both models: the current material weight in the hopper (rWeightNETTO) and the gate opening percentage (rSpoutOpen).

Data Collection Setup and Protocol:

Measurements on the physical model were conducted for two initial material weights (5 kg and 10 kg) and four gate opening levels (25%, 50%, 75%, and 100%). To compensate for physical stochasticity, five consecutive repetitions were executed for each configuration, yielding 40 physical measurement runs in total. The physical Siemens S7-1200 PLC sampled and logged sensor data at a high-resolution cycle time of 10ms directly into internal memory trace buffers.

Dataset Characteristics, Volume, and Integrity:

Each experimental run recorded data over a duration of 8 to 12 seconds, resulting in approximately 800 to 1,200 data rows per run for the physical setup (totaling ~32,000 recorded data points across all physical trials). Inspection of the raw CSV exports confirmed 0% missing values (no dropped frames or missing timestamps), attributable to the local deterministic logging buffer of the SIMATIC controller.

Raw physical measurements exhibited characteristic signal noise (transient fluctuations of $\pm 0.15\text{kg}$) caused by mechanical vibrations transmitted to the single-point load cell suspension (EMS 100-5kN) and minor granular settling of the gravel bulk material (density $\rho = 1,550\text{kg/m}^3$). Rather than applying destructive low-pass filtering that could alter temporal dynamics, ensemble arithmetic averaging across the 5 runs per configuration was applied to compute a representative mean physical time series. An example of the measured time profile is shown in Fig. 2.

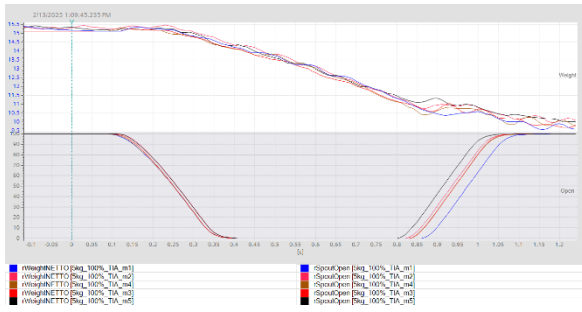


Figure 2. Discharge of 5 kg batch from the physical model at 100% opening.

Simulation Data and Synchronization: In the SIMIT behavioural model, a single execution run per configuration was sufficient, as the mathematical model operates deterministically without external environmental noise. The simulated PLC in SIMIT executed at a fixed sampling slice of 100ms.

Following export, physical datasets (10ms sampling) were synchronized with virtual datasets (100ms sampling) by performing linear interpolation on physical time series to align with a unified 100ms time grid. Temporal alignment was established by defining $t = 0\text{ms}$ as the exact instant when the gate actuation signal ($rSpoutOpen > 0\%$) was triggered. This standardized dataset provided a rigorous basis for evaluating model accuracy in **RQ1** and interface fidelity in **RQ2**.

7 Results

The consistency between the physical and behavioural models was quantitatively evaluated using the Pearson correlation coefficient for the time series of weight and gate opening. Table 2 presents selected measured values for the reference configuration: a 5 kg batch with 100% gate opening.

Table 2. 5 kg batch at 100% gate opening – selected values (Pikna, 2025)

Time [ms]	Weight physical [kg]	Weight virtual [kg]	Opening physical [%]	Opening virtual [%]
-800	15.32	15.10	100.00	100.00
-400	15.15	15.10	100.00	100.00
0	15.14	15.10	100.00	100.00
400	13.81	14.05	0.00	0.00
800	10.84	12.70	48.45	0.00
1200	9.77	11.12	100.00	0.00
1600	9.92	9.94	100.00	100.00
2000	9.88	9.36	100.00	100.00

Weight Correlation: 0.947 | Gate Opening Correlation: 0.489

An examination of the time steps in Table 2 clarifies the physical mechanisms underlying the discharge process:

- **Static phase** ($t = -800\text{ms}$ to 0ms): Both physical and virtual systems register static full-capacity weight (15.14kg physical vs 15.10kg virtual). The slight initial offset (0.04kg to 0.22kg) stems from residual mechanical settling of the bulk material against the hopper walls and load cell tare tolerance.
- **Initiation of discharge** ($t = 0\text{ms}$ to 400ms): Upon command execution at $t = 0\text{ms}$, the valve actuates. By $t = 400\text{ms}$, physical material weight decreases to 13.81kg, while virtual weight decreases to 14.05kg. The physical system shows earlier material flow initiation due to immediate opening of the pneumatic seal before the continuous analog position sensor fully records movement.
- **Transient discharge phase** ($t = 800\text{ms}$ to 1200ms): At $t = 800\text{ms}$, physical gate opening reaches 48.45% and physical weight drops to 10.84kg. In contrast, the virtual model records 12.70kg. This lag occurs because the virtual model utilizes a linear ramp block to emulate gate motion, whereas the physical FESTO pneumatic cylinder undergoes non-linear pressure buildup, accelerating faster during the initial stroke. By $t = 1200\text{ms}$, physical gate opening reaches 100% while the virtual gate ramp finishes slightly later, causing temporary variance in flow rates.
- **Completion and steady state** ($t = 1600\text{ms}$ to 2000ms): As the gate reaches full closure/opening, physical weight stabilizes at 9.88kg and virtual weight at 9.36kg (representing the remaining batch inside the hopper). Both curves converge closely, achieving a high overall weight correlation $r = 0.947$.

Based on the analysis of all eight configurations, the following summary results were achieved:

- **Weight profile correlation:** range 0.947 – 0.994, arithmetic mean **0.977**.
- **Gate opening profile correlation:** range 0.412 – 0.956, arithmetic mean **0.679**.

A critical evaluation of these trends directly addresses **RQ1**:

- **Intermediate Openings** (50% and 75%): These configurations yielded the highest weight correlations (>0.985). At moderate flow cross-sections, gravel flow matches Bernoulli's ideal fluid assumption closely, maintaining steady quasi-continuous discharge without severe velocity spikes or mechanical clogging.
- **Small Opening** (25%): The lowest weight correlation occurred at 25% opening. At restricted cross-sections, internal granular friction, particle interlocking, and temporary arching (bridging) decrease the effective discharge velocity below theoretical fluid predictions—phenomena not captured by basic Bernoulli equations.

- **Gate Actuator Discrepancy** (100% opening / 5 kg batch): The lower gate opening correlation (0.412 - 0.489) is attributed to pneumatic cylinder dynamics. Under fast actuation, air compressibility, solenoid switching hysteresis, and mechanical friction cause non-linear acceleration that the simplified linear SIMIT ramp block does not replicate. However, because batch dosing algorithms rely primarily on cumulative material weight rather than sub-second valve position, this gate dynamic discrepancy does not impede control code validation.

8 Discussion

The high average correlation of weight profiles (0.977) directly answers **RQ1**, confirming that the mathematical model derived from Bernoulli's equation accurately describes the discharge dynamics of bulk material from a frustum-shaped hopper. The model correctly captures the dependence of the flow rate on both the material level and the gate opening percentage.

The lower average correlation during the gate opening and closing process (0.679) results from the simplified ramp model, which does not account for varying load pressures on the gate at different opening percentages. In the physical system, the pneumatic cylinder overcomes significantly higher material pressure at a 25% opening compared to a 100% opening, leading to distinct gate movement dynamics. However, this deviation does not fundamentally impact the model's utility for verifying dosing algorithms, where the precision of the final batch weight is decisive, rather than the gate's movement dynamics.

Another source of deviations was the mechanical design of the physical model: the hopper was attached to the support frame solely through the EMS 100-5kN load cell, causing all mechanical vibrations generated by the bulk material to be transmitted directly into the measurement path. The hopper was mechanically suspended at a single point, allowing for slight tilting during uneven material distribution during discharge. These effects are not accounted for in the behavioural model, which explains the noise visible at the start of the physical model's measurements.

Regarding **RQ2**, the practical implementation confirmed that native integration between SIMIT and TIA Portal significantly simplifies machine-level virtual commissioning. Shared PLC variable tables eliminated the need for manual tag mapping or middleware configuration. Signal exchange operated deterministically without observed communication latency during 100ms simulation steps. The key advantage of the proposed approach is the full parameterizability of the model: changing any geometric parameter of the hopper (e.g., a different height while maintaining the base dimensions) does not require a new physical model – it is sufficient to adjust

the relevant input values in the Frontend. For hoppers of different geometric shapes, such as cylindrical or conical hoppers, a change in the computational equations in the Backend is sufficient without the need to redesign the entire model architecture. (Wu et al., 2023)

While the present study validates the core behavioral model using Bernoulli's equation across 8 different physical configurations, further mathematical enhancements are necessary to overcome observed edge-case deviations. Future iterations of the mathematical model will incorporate Discrete Element Method (DEM) physics to capture granular material dynamics (such as particle friction and arching effects during partial gate openings) as well as non-linear pressure dynamics within the pneumatic actuator.

9 Conclusion

The presented behavioural model of the bulk material hopper was successfully designed, implemented in the SIMIT environment, and experimentally validated by comparison with a physical hopper model at SKARTEK s.r.o.

In response to **RQ1**, experimental validation demonstrated an average weight profile correlation of 0.977 across eight measurement configurations, proving that the Bernoulli-based mathematical model provides sufficient accuracy for testing PLC dosing logic without physical prototypes.

In response to **RQ2**, the native coupling between SIMIT and TIA Portal demonstrated seamless tag synchronization, zero-latency signal exchange, and rapid parameter modification, proving that dedicated native simulation environments provide superior workflow efficiency for machine-level virtual commissioning compared to generic simulation tools.

The key advantage of the behavioural model over a physical prototype is significantly lower cost, shorter preparation time, and easy parameterization for various hopper variants. When developing projects involving multiple hoppers with different dimensions, it is sufficient to adjust the geometric parameters in the virtual model without the need to build new physical prototypes. This directly fulfills the principles of Industry 4.0 – shortening lead times, reducing development costs, and increasing the quality of the final control algorithm.

In the future, the authors are encouraged to expand this methodology through additional case studies involving different industrial hopper geometries (e.g., cylindrical, conical, and asymmetric hoppers) and various bulk materials with distinct flow properties. Extending the digital twin framework to multi-hopper production lines and integrating real-time DEM simulations will provide even stronger empirical evidence for automated virtual commissioning across broader Industry 4.0 applications.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Google Gemini in order to assist with English language translation, grammatical refinement, formatting, and structural revision based on peer review feedback. After using this tool, the authors reviewed, critically evaluated, and edited the content as needed, and take full responsibility for the content of the published article.

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