Digital Twins in Engineering, DTE 2027
March 8-12, 2027, Yokohama, Japan

PHYSICS-INFORMED, DATA-DRIVEN DITIAL TWINS OF GRANULAR MATERIALS

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ABSTRACT

This minisymposium (MS) focuses on the integration of physics-based modeling and data-driven methodologies to develop digital twins for granular materials across scales—from particle-level interactions to industrial and geotechnical systems. Granular media pose unique challenges due to their discrete nature, complex flow behavior, and sensitivity to initial and boundary conditions. Traditional simulations (e.g., DEM, MPM) offer high fidelity but remain computationally intensive, while purely data-driven approaches risk violating physical constraints.

The MS objectives are: (i) to present recent advances in hybrid frameworks that embed physical information (e.g., conservation laws, contact mechanics, pore collapse models) into machine learning architectures (e.g., temporal graph neural networks, operator learning, encoder-decoder models); (ii) to explore digital twin implementations for real-time prediction, material tracking, and process optimization in mining, rotary kilns, blast furnaces, and warehouse logistics; and (iii) to discuss methods for uncertainty quantification, model reduction, and validation using X-ray microtomography (CT), 3D particle reconstruction, and in-situ experiments.

Key topics of this MS include: CT-based digital twins, physics-constrained deep learning simulators, surrogate modeling for multiscale granular flows, digital twins for asteroid regolith and space manufacturing, carbon-aware warehouse management, and the role of additive manufacturing and large vision models in generating high-fidelity grain morphologies. The MS aims to bridge computational mechanics, materials science, and industrial engineering, fostering discussion on scalable, trustworthy digital twins that respect physical laws while leveraging real-time data.