# Virtual Reality and Sim-to-Real Development of Metallurgical Operations

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**Abstract**

Previous developments in the simulation of metallurgical operations led to the representation of alternating modes of operation. These operating modes are initially described as mass balances within a system of nodes, representing the components of the metallurgical plant, to a higher or lower degree of resolution, depending on the data available, and the objective of the simulation. As an engineering project progresses, the modes are represented in increasing levels of detail, focusing on the most critical aspects, i.e., the critical opportunities driving a project forward, and also the critical risks and threats that are obstructing progress. Whereas a high-level representation considers dynamic mass balances, and the fluctuating material contents of reactors (grinding mills, flotation cells, thickeners, etc., in the case of mineral concentrators, or furnaces and ladles in the case of smelters), a detailed representation may eventually benefit from immersive experiences, within a computer-powered virtual reality (VR) representation of the plant. The data generated by operators and engineers in VR can inform continuous improvement and reengineering projects for existing plants, as well as the later stages of a greenfield project (detailed engineering and ramp-up). Furthermore, VR representation of metallurgical plants is of pedagogical value for engineering students, likely impacting how future metallurgical engineers will execute their projects. The current paper presents the progress and feedback from a VR development of a fictitious concentrator and describes how these efforts could be merged with the simulation testing of machine-learning-enabled control systems and other emerging challenges in mineral processing and extractive metallurgy.

**Keywords**

Virtual reality · Extractive metallurgy · Mineral processing · Discrete event simulation · Machine-learning enabled control strategies · Modes of operation · Active learning · Operational readiness

## 1 VR and Sim-to-Real as a Next Step in Metallurgy 4.0

The 2021 Conference of Metallurgists was held entirely online and, fittingly, included the symposium *Industry 4.0: Sensors, Control, Automation, and the Use of Digital Information*. Indeed, the era of COVID-19 had lasting impressions on the metallurgical industry (and society as a whole) and was an accelerant for the disparate movements that constitute Industry 4.0.

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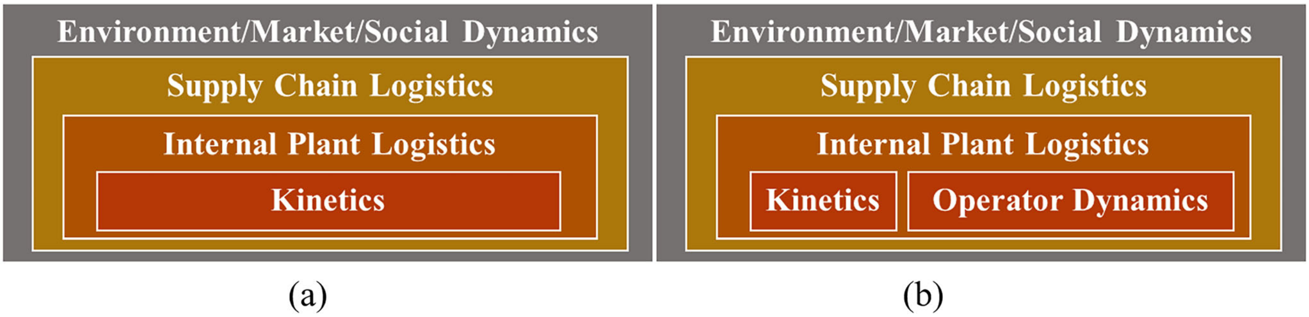


**Fig. 1** (**a**) Previous work [9] distinguished between kinetics that occur *within* unit operations and logistics that occur *among* unit operations. (**b**) Operator dynamics is like another "kinetics"

Approaches combining process control and machine learning were presented in 2021 [1–7], including the concept of a digital twin [2], however, the potential immersive virtual reality had not been addressed.

Previous work by Navarra et al. [5, 7–9] developed a project-oriented methodology for developing discrete event simulation (DES) for metallurgical and mining systems, considering discrete rate simulation (DRS) as a particular kind of DES that is especially well-suited for the early phases of multiphase engineering projects. Within the conceptualization phases of an engineering project, each competing option can be characterized by system-wide mass balances. These balances consider tonnages of incoming and outgoing streams, including valuable by-products, and undesirable emissions into the environment, with the main system components represented as nodes. As the project progresses into further phases, increasing levels of detail are incorporated, replacing the simplifications and refining the assumptions, to represent the critical opportunities that are driving an option forward, and the critical risks or threats that are disfavoring it in relation to other options. Many of the critical risks are not captured by a *static* mass balance, since it is *dynamic* spiking that would cause a system to approach or exceed its design capacity [7, 8]. There is thus a need to transition from a static mass balance, eventually into a dynamic mass balance, and DRS is debatably the most elementary form of dynamic mass balance; it represents fluctuations in the level stockpiles, furnaces, and other nodes through piecewise linear functions, i.e., discrete rates. For mining systems, geostatistical computations [10] represent upstream variation in incoming feeds which affect these rates, and the supply chain logistics that feed metallurgical plants. Figure 1a is adapted from Navarra et al. [9] relating logistics and kinetics. The explicit representation of discrete production batches (as in Peirce-Smith converting, [9, 11]) or the departure and arrival of trucks, ladles, and other containers requires an extension beyond DRS into a proper DES. At a low resolution, different modes of operation are characterized by different dynamic mass balances and the triggering conditions that would cause mode changes. At an especially high resolution, the behavior of operators may be a different kind of "kinetics" as depicted in Fig. 1b. In establishing standardized operator tactics, VR-based experiential learning can have an analogous role to laboratory-based thermochemical experiments.

The data obtained from VR-based simulated metallurgical environments can be used to parametrize more expansive system-wide simulations. Previous work by Navarra et al. incorporated machine learning algorithms within DRS frameworks [7, 10, 12]. Variable aspects of plant behavior can be subject to reinforcement learning [13], taking into account the coordinated responses of operators, constituting the so-called sim-to-real approach. This approach is already prevalent in the development of robotics within manufacturing [14], especially in warehouses [15], and has emerging applications in advanced control of chemical engineering plants [13]. Future metallurgical plants will be supported by machine-learning-enabled control strategies that are designed to perform synergistically with expert operators and engineers. The refinement of these approaches will benefit from virtual reality as a method of capturing operator behavior and detecting the variable ranges of behavior that can be enhanced.

Detailed engineering phases already result in voluminous quantities of CAD objects, as well as piping and instrumentation diagrams (P&ID), and diligent hazop studies. While these are already being used as input for 3D representations for metallurgical and mineral processing plants (Fig. 2), there seems to be an untapped potential in metallurgical plants to use VR to promote operational readiness, both at the initial ramp-up of a greenfield project, and later on for continuous improvement initiatives and reengineering, as well as routine operator training.

Prior to any convincing contribution that VR and sim-to-real may have in machine-learning-enabled control strategies of metallurgical plants, VR would likely require a much broader adoption at the pedagogical level. VR representation of industrial plants is already of use for engineering students as well as operators [16] and will likely impact the way future

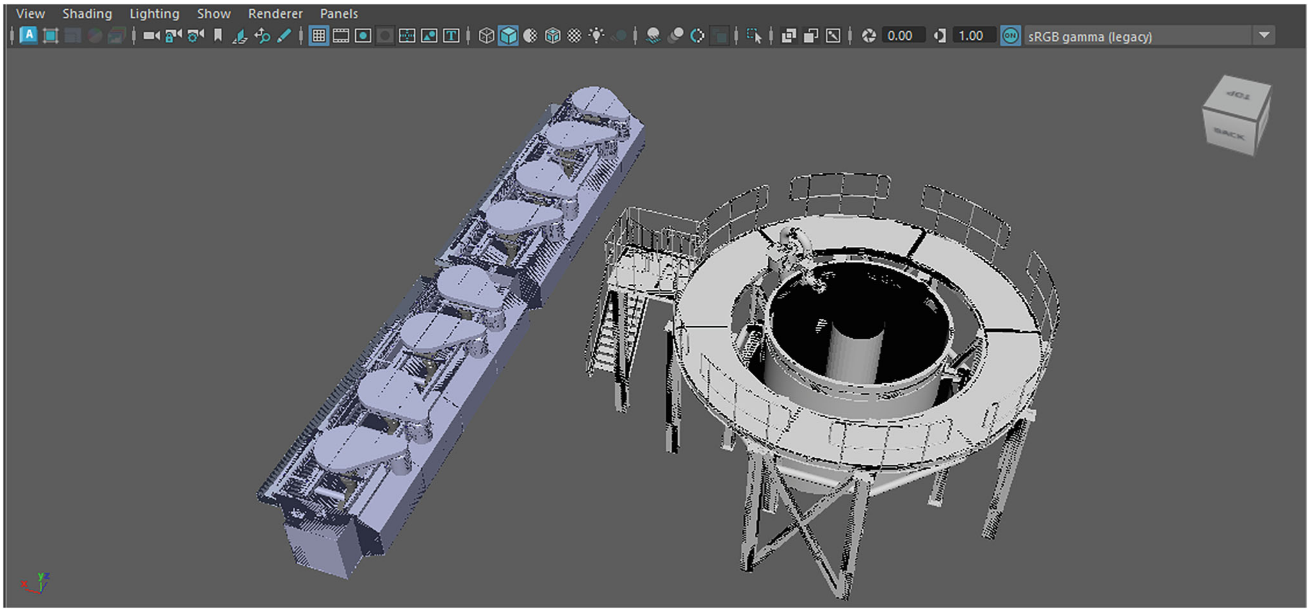


**Fig. 2** Screenshot of a bank of flotation cells (left) and the holding structure for a hydrocyclone (right) as seen in Autodesk Maya

**Table 1** Participants in the brainstorming session of February 21, 2024

| Participant | Professional role | Perspective |
|---|---|---|
| C. Ciriello | Principal consultant for *Analyze and Improve, Inc.* | Leader in continuous improvement initiatives and operational readiness in mineral processing plants |
| B. Hanel[a] | Computer scientist and expert programmer | Background in game development and machine learning, currently developing VR tours for industrial processing plants |
| S. Huberman | Professor of chemical engineering | Multidisciplinary interests including mechanical and chemical engineering processes, and molecular computations, and teaches instrumentation |
| K. Pearce | Mining engineering with expertise in tailings management | Experience at two mine sites. Familiarity with engineering software for 3D visualization of tailings, operational simulations, and gaming |
| N. Peters | Professor of chemical engineering | Expert instructor and consultant in chemical process design and is assisting in the development of VR |
| N. Razavinia | Associate Director of Academic Programs (Faculty of Engineering) | Leader in accreditation processes and pedagogical initiatives in engineering; holder of a VR-related grant |
| T. Sun[a] | Mining engineering student pursuing a minor in computer science | Has completed the requirements for the mining engineering co-op and is studying computer animation as part of a minor |
| L. Theiss[a] | Mining co-op liaison manager | Prepares students for internships and employment upon graduation; teaches professional etiquette, organizes field trips, and info sessions |
| K. Waters | Professor of mining and materials engineering | Researches and teaches mineral processing. Leads the McGill Mineral Processing Group, and the mineral processing lab |

[a]Participated in the January 18 trip to Agnico-Eagle's Laronde Metallurgical Complex, along with Navarra

metallurgical engineers execute their projects, perhaps in unpredictable ways. Presumably, it will impact how plants are operated, as well as how they are designed. The following section focuses largely on the more immediate opportunities to enhance pedagogy within the McGill Faculty of Engineering.

## 2 Brainstorming on the Pedagogical Value of VR Training for Mineral and Chemical Processing and Extractive Metallurgy

Content from this section follows from a brainstorming session held on February 21, 2024, including the authors as participants, and Prof. Norman Peters who is the instructor at McGill University for the chemical engineering capstone project and will be incorporating a VR representation of a $ClO_2$ plant into his Fall 2024 offering. Table 1 summarizes the perspectives that were brought by the different participants.

Several of these participants had partaken in a field trip to the Laronde Metallurgical Complex on January 18, 2024, owned by Agnico-Eagle. Other than Navarra who assisted in guiding the tour, and the plant superintendent Jean-Sébastien Labonté who led the tour, the participants had not previously toured a flotation plant. The intention was for Hanel, Sun, and Theiss to imagine what a first-year student would experience on such a field trip, after having been briefly exposed only to textbook pictures of the equipment, and PowerPoint slides. This immersion is highly rewarding but is nonetheless overwhelming as students struggle to link their classroom exposure to onsite exposure. Preparation for onsite tours could include VR, thus training students to make stronger visual associations between the lecture content and the eventual visit to a real plant. Also present on the tour was Mrs. Marisa Vincelli who is a human resources specialist at Agnico-Eagle who interfaces with the McGill co-op program; she had years of experience recruiting concentrator staff but had not previously visited a concentrator.

The brainstorming session was held over Zoom and was recorded. It lasted for 1 h, and contemplated the following two questions:

1. What connections do you see between your roles (in industrial settings, labs, offices, etc.) and VR-enabled engineering/training for chemical/mineral/metallurgical processes?
2. How do you see the potential for embedding mathematical models (first-principals, data-driven, combinations) within VR in connection to engineering, operations, and pedagogy?

   Following the 1-h session, a third question was transmitted by email:
3. Undergraduate engineering students as well as process operators may favor visual explanations rather than purely text-based learning,
   - Students may have a good theoretical background but struggle to visualize the scale and complexity of actual process plants
   - Process operators have a deep knowledge of operations but lack a theoretical understanding of the reasoning behind the processes

   How do you see the common interests, and fusion of resources, between financially driven processing companies, and the enhancement of learning outcomes, vis-à-vis funding VR initiatives?

In summary, the first question integrates perspectives (Table 1), the second emphasizes engineering mathematical models in line with sim-to-real approaches, and the third seeks to conceive industrial partnerships to address funding issues.

In answering the integrative question (Question 1), we considered that training is a major part of operational readiness and that start-ups for metallurgical plants are often surprisingly weak. For instance, surface mine equipment operators benefit from many hours of training to operate excavators, trucks, etc., before being exposed to actual equipment, but similar practices are not usually undertaken by process operators. Repetition of operations that are highly variable or complex can consolidate standard operating practices. Moreover, there is a need to practice scenarios that are comparatively infrequent but are nonetheless critical, including rescue drills and other emergencies. VR can be important for metallurgical operators, but also engineering co-op students who will perform a work term as an operator. Navarra's experience in his first co-op work term in the summer of 2000 at the Louvicourt Concentrator, in which he had worked as an operator, had been a discussion topic during the January field trip. Following Navarra's completion of his undergraduate program in Materials Engineering at McGill in 2005, there seems to have been fewer co-op internships to assist the plant operators. The perspectives that mining and materials students gain in such an experience are highly sought by employers, and companies such as Agnico-Eagle are motivated to foster these experiences. VR can help develop the interest and confidence of students to attain such experiences.

In further discussion related to Question 1, it was remarked that software tools such as Autodesk Maya are clearly within the existing skill set of typical engineering students, who already use CAD programs such as Autocad. For instance, STEP files are a common file type on the GrabCAD website, which are generated from AutoCad, Autodesk Investor, and SolidWorks; they can be converted to the FBX file format that is recognizable by Unity. It is surprising how much industrial equipment is available in online repositories (Fig. 2), either freely on GrabCAD or for a small fee on TurboSquid. This allows for basic development of VR experiences but falls short of having properly sized units (which would be the subject of a true engineering effort, e.g., an undergraduate capstone project). Gaming engines such as Unity and Unreal require an additional level of training, but could be worthwhile for interested students to prepare operational scenarios in the spirit of peer teaching and peer learning. Interestingly, since students each have different co-ops, hence different experiences, student-led development of VR scenarios could be an enriching mechanism for students to *collectively* benefit from the various *individual* co-op experiences. Moreover, those especially motivated students who participate in the programming of the scenarios can develop transversal skills, not only in programming but also in the formulation and resolution of operational problems. As mentioned previously, there is an underutilized connection between the preparation of VR scenarios and the detailed engineering of metallurgical plants.

In teaching undergraduate students mineral processing and extractive metallurgy, VR experiences can show students plants from around the world, at opportune times in the semester, immediately before or after, e.g., a particular lab experiment, or discussion of a certain equipment or process. Similarly, in teaching a course on instrumentation, students may struggle to relate lab-scale devices (pH sensors, thermocouples, etc.) to the large-scale unit operations that they will be exposed to later in their studies. Incorporating VR experience into an instrumentation can be an effective early exposure to these unit operations, without yet having rigorously studied topics such as chemical kinetics and transport phenomena.

The main concern in promoting VR-based initiatives within the university setting is to attain interest and commitment from professors, who already have well-established course material that is mostly well-received. The direct participation of professors is required to determine how exactly VR and other technologies can be incorporated into the program. For instance, the subject and versatility of Prof Peters allows him in particular to experiment with VR within an offering of the Chemical Engineering capstone project, and then potentially to expand it in future years. But its proper execution requires additional effort on his part, beyond what has already given reliably positive learning outcomes. The earlier adopters of VR-based education seem to rely on synergistic benefits with other forms of experiential learning, which offsets some of the risk, e.g., Navarra and Theiss can use VR-based experiences to foster new co-op experiences that would expose engineering students to plant operators, and Waters and Huberman can formulate VR-based extensions of existing laboratory experiments. Navarra has even a further synergistic interest, which is to relate his research in system dynamics research (mining systems, mineral processes, and metallurgical plants) with VR-based representations of operator scenarios. It is only a minority of professors that have this synergistic interest.

## 3 In-house Sim-to-Real and VR Development of Mining, Mineral Processing and Metallurgical Operations

Final comments regarding Question 1 mentioned the relevance of a game architect. Online games (e.g., Factorio [17]) include underlying mathematical models that control system dynamics and are engaging to the user. Upgrading such games into engineering educational tools may simply be a matter of mathematical modeling, and documenting the assumptions and simplifications. One can imagine a VR immersion in which an operator alters a particular part of a mineral processing plant, which has repercussions that cascade to “offscreen” aspects of the process, including compensatory actions by other operators (which may or may not be explicitly represented). This effectively is a sim-to-real approach, even though this terminology had not been mentioned during the brainstorming session. These “offscreen” aspects can be a digital twin of a real plant.

Question 2 of the brainstorm distinguished between two types of mathematical models, namely first-principles models, and empirical models, and also considered the potential combinations of these models; the same characterization had been considered by [16]. First-principles modeling can include contact dynamics of operators using heavy equipment to transport heavy loads, e.g., a crane operator transporting ladles of molten matte; VR crane dynamics that are based on first principals have already been developed at McGill [18] and could well be adapted for metallurgical contexts. In contrast, the direct incorporation of a discrete element model of comminution dynamics into a VR, e.g., to represent a SAG mill, would be computationally expensive, and would not seem credible given the underlying doubts of what actually happens in a SAG; in this case, empirical models may be a better choice, including regression models that link incoming F80 and outgoing P80 values as a function of operational settings.

An effort to create a VR tour of a mineral concentrator is currently underway within the McGill Faculty of Engineering, depicted in Fig. 3. These efforts complement Navarra’s interest in simulation training for tailings management (Fig. 4), related to VR research in terramechanics that is ongoing at McGill University [19]. Both of these directions are extensions of previous work in DES and DRS [5, 7–9], which ideally will foster closer ties to industrial installations and discussions with operators (and perhaps some nostalgia for Navarra’s undergraduate co-op experiences from the Summer of 2000).

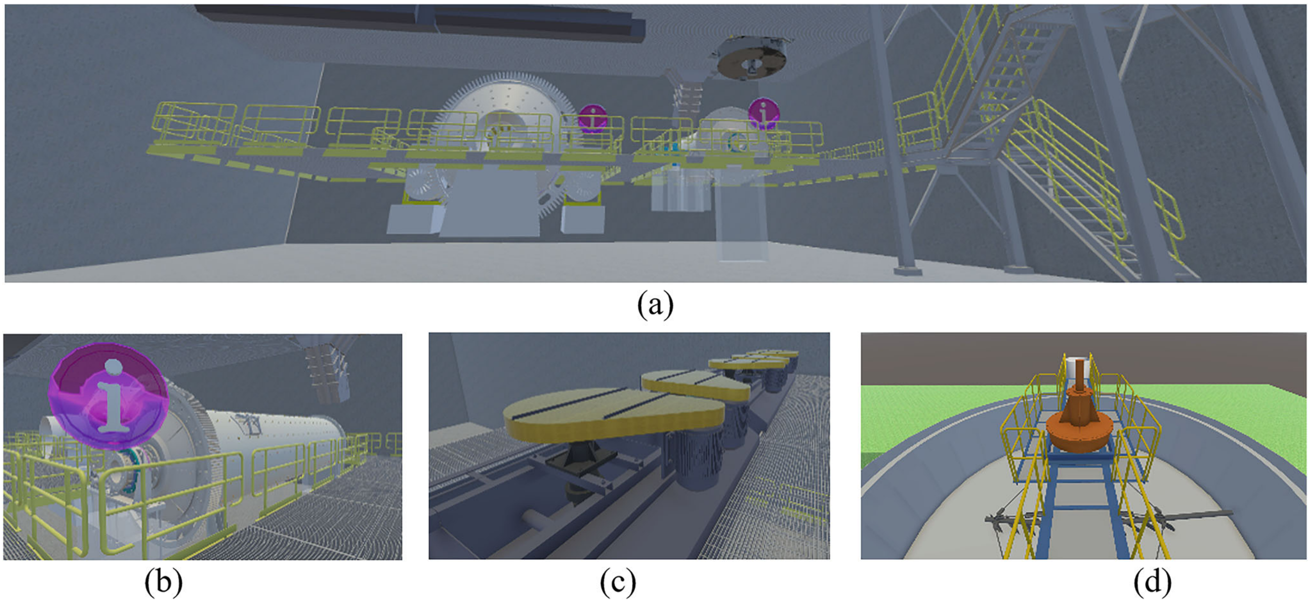


**Fig. 3** Screen captures of the Unity gaming engine, showing the progress in visiting a flotation plant, as of March 7, 2024: (**a**) approach to grinding circuit, (**b**) close-up of an information bubble that will explain ball mills, (**c**) a bank of flotation cells, (**d**) peering down into a thickener

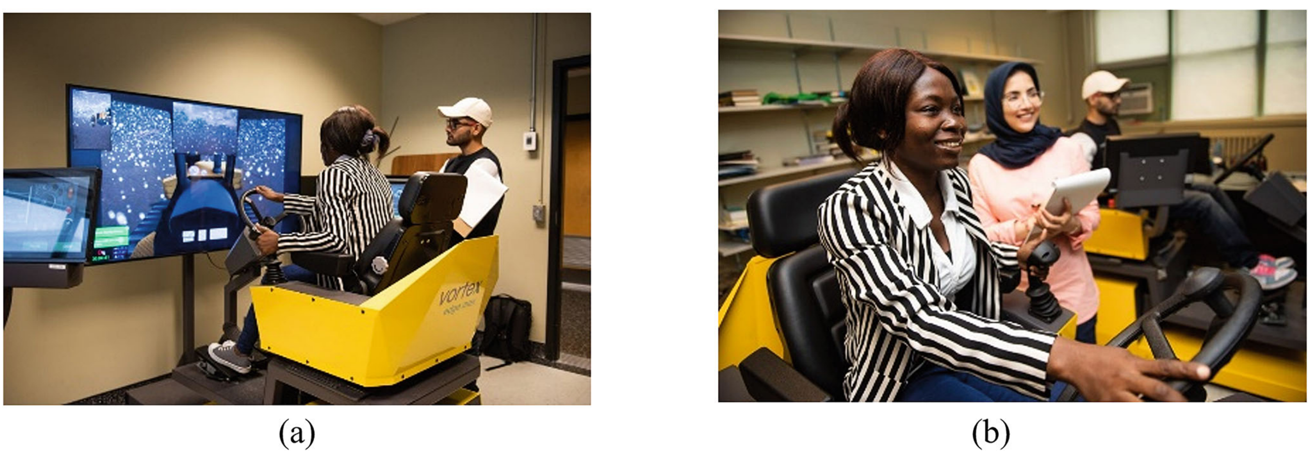


**Fig. 4** Simulators used to simulate earthmoving operations comparable to tailings management operations, (**a**) view of robotic seat apparatus in Navarra's office, and (**b**) view of trainee

## 4 Future Work

For VR and sim-to-real to attain tangible results for mineral processing and metallurgical plants, more research and development are required. However, these efforts foster technical skills in engineering students, such as stronger programming and mathematical modeling, as well as problem formulation and resolution, which are relevant to engineering design. These efforts can also foster closer discussions with mining and metallurgical companies, including discussions with operators addressing operational problems which have previously been underexplored.

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