AN INTEGRATED APPROACH TO DEVELOPING SAFE AND EFFICIENT PLANT LAYOUTS

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Abstract—*A facility's layout can significantly affect the success of its envisaged operation in terms of safety, lifecycle cost, and environmental impact. This paper presents an innovative approach to predicting and measuring the traffic characteristics of a given layout in terms of these three factors. Derived from lessons that Bechtel has learned in the process of developing numerous plant layouts and analyzing resources, this new approach allows the quick comparative analysis of competing layouts to arrive at a safe, lean, and green plant configuration.*

To illustrate how the approach works, this paper examines its application of safety by design and lean manufacturing techniques to designing the layout of a fully integrated aluminum complex. Aluminum smelter layout development usually involves dealing with an integrated mix of operations and services (smelting, carbon anode formation, metal casting, material handling, etc.). Integral to this approach are the design of access roads, choice of transportation modes, and planning of resources, as discussed throughout the paper.

Keywords—*layout development, lean design, simulation, traffic*

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INTRODUCTION

Bechtel's Aluminum Center of Excellence (ACE) is the repository of the company's institutional knowledge, technical capability, historical information, and lessons learned on the design and construction of smelter projects. ACE's mandate is to deliver value to projects by applying this knowledge and skills, focusing on sustainable design. The integrated approach to developing safe and efficient plant layouts presented in this paper was developed by ACE and funded by a Bechtel internal technical research grant[1].

A facility's layout can significantly affect its long-term success in terms of both safety and its ability to compete successfully in the marketplace. In addition, the investment costs associated with building a given layout are substantial. Early layout development and finalization offer a clear advantage to the project from both a cost and a schedule perspective, compared to finalizing the layout later, during project execution.

Layout development requires a complete understanding of the operational aspects of a particular plant. The operation of an aluminum smelter, for example, relies on interactions between customer and supplier facilities to convey people, products, and materials (PPM), with the road network directly affecting operational safety and efficiency. As a consequence, a quick and effective approach to assessing layout safety and efficiency early during the design phase is required.

Typically, laying out traffic-intense facilities such as an aluminum smelter involves having a detailed understanding of traffic interactions and behavior. A known approach is to statically map the layout's characteristics, identify roads and intersections, assign routes to traffic, and calculate average inter-arrival times.

ACE's use of this evaluation method revealed that a greater awareness of safety and efficiency was needed, and that it should be based on a better understanding of the dynamic characteristics of plant traffic flows. Discrete-event modeling (DEM) was chosen as a natural fit for PPM traffic flow problems. [1] **Figure 1** illustrates the application of DEM to envisaged traffic at a plant shuttle bus station during a shift change.

Previous case studies have demonstrated the complexity of the different issues arising throughout the layout development process. Based on DEM, ACE created a systematic approach—referred to in this paper as the

1 Technical Approach for Safe and Efficient Plant Layout Development—a mini-grant study performed in 2010 by Rafael Pires and Laszlo Tikasz under the Bechtel Technical Grant Program.

Safety is an integral part of corporate social responsibility.

ABBREVIATIONS, ACRONYMS, AND TERMS

ACE	Aluminum Center of Excellence (Bechtel)
BDD	basic design data
CAD	computer-aided design
CCF	comparative cost function
CO_2e	carbon dioxide equivalent
DEM	discrete-event modeling
FMEA	failure mode and effects analysis
IATA	International Air Transport Association
LOS	level of service
PPM	people, products, and materials
RPN	risk priority number
TAC	Treatment of Aluminum in Crucible

Integrated approach—to automating data transfer and reducing the cycle time needed to assess a given layout's safety, efficiency, and CO_2 equivalent (CO_2e) emissions related to the traffic network.

Bechtel's adoption of the integrated approach has delivered value by quickly simulating and analyzing plant layouts and assessing the effectiveness of proposed improvements.

LAYOUT DEVELOPMENT

It is well known that the layout of a traffic-intense plant affects not only the project's capital cost but—more importantly—decades of plant operations. The development of a safe, efficient layout requires a collection of tools and expertise to design out the potential for accidents, waste, and uncertainties related to PPM conveyance between customers and suppliers.

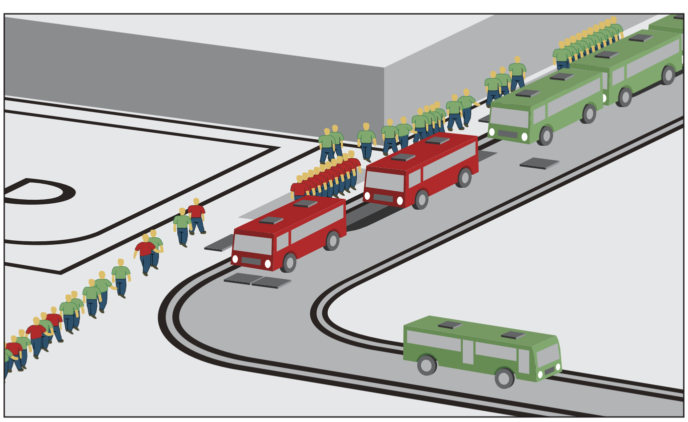

Figure 1. Example of Plant Shuttle Bus Station Traffic During Shift Change

Lean manufacturing and Six Sigma tools provide guidance on streamlining layout development initiatives. [1] Proper application of these tools during initial project definition helps to freeze the layout early, thereby avoiding rework, minimizing risk, and providing certainty to the design team and future plant operators that the layout is safe, lean, and green (see **Figure 2**).

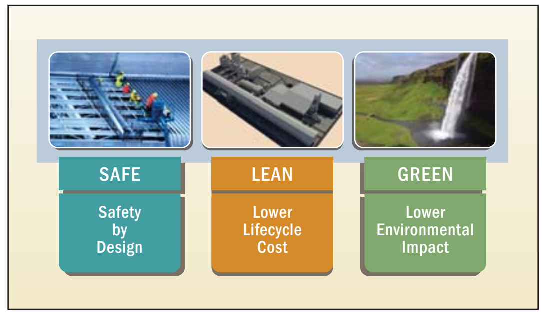

Figure 2. The Safe—Lean—Green Principle

Safe—Safety by Design

Safety is an integral part of corporate social responsibility. There is a clear connection between operational safety and the level of quality achieved. [2] A safe plant configuration lays the early foundations for developing an organizational culture that values behavior-based safety.

The objective of designing safety into plant layouts is to minimize the potential for accidents. Safety by design reduces the likelihood of accidents over a plant's lifecycle. As mentioned, DEM complements both layout development and optimization studies. It provides a way to mimic and monitor the expected operation and to collect data for further analyses. A failure mode and effects analysis (FMEA) can then be applied to estimate the risk of accidents at any particular intersection in the plant's road network.

A variety of operational factors influence the overall safety of a plant layout. These factors include intersection [3] and vehicle types, work schedules, and transportation modes. An FMEA is used to design and score individual intersections by incident severity, occurrence, and detection factors that are combined into risk priority numbers (RPNs). The RPN of any particular point of a layout is that point's safety measure.

Lean—Lowest Lifecycle Cost

Designing an efficient operation requires applying lean principles and tools to identify and eliminate waste and streamline PPM flow. In theory, efficient operations can maximize productivity with minimum waste, effort, and expense. [4] However, variations generated by transient operational conditions directly affect and reduce efficiency.

DEM is used to predict the dynamic response of a particular operation, including traffic and material conveyance and storage, to ensure that the proposed configuration can meet customer needs during normal, maximum, and upset operating conditions. [5] During overall layout development, DEM is used to mimic traffic flows and operations to validate the number of vehicles, load/unload stations, and inspection lanes; parking lot requirements; inventory requirements; etc., to minimize the risk inherent in the overall plant layout, thereby offering a lower lifecycle cost.

Green—Environmental Impact

A layout's environmental performance is influenced by PPM movement. The road network design, PPM conveyance between customers and suppliers, and traffic type segregation all affect the distances driven by vehicles. As a consequence, traffic-related emissions are also affected. During DEM simulation, the number of vehicles required and the distances driven per vehicle are confirmed, not only to understand the operational cost related to traffic, but also to estimate CO_2e emissions.

THE INTEGRATED APPROACH

Bechtel's need to quickly and effectively develop safe, lean, and green layouts led to ACE's integration of the various concepts previously mentioned into an automated platform. This new platform automates data transfer and speeds layout assessment. **Figure 3** outlines the structure of the integrated approach and the connections between the layout analysis phases.

The integrated approach was assembled by coupling and partially integrating proven tools.

The integrated approach was assembled by coupling and partially integrating proven tools such as computer-aided design (CAD) drawings, the plant basic design data (BDD) model, PPM flow mapping, dynamic modeling (using Flexsim® simulation software), FMEA, and a generalized comparative cost function (CCF). The resulting platform automatically collects projected plant layout and operation parameters and links them in a dedicated input data set. This data set is then used to specify, construct, and run the plant dynamic model. The simulated plant operation is monitored, and data from simulated scenarios is collected and automatically exported to the same data set.

The quantitative analysis provided by the platform takes into account the dynamically changing conditions of the projected traffic,

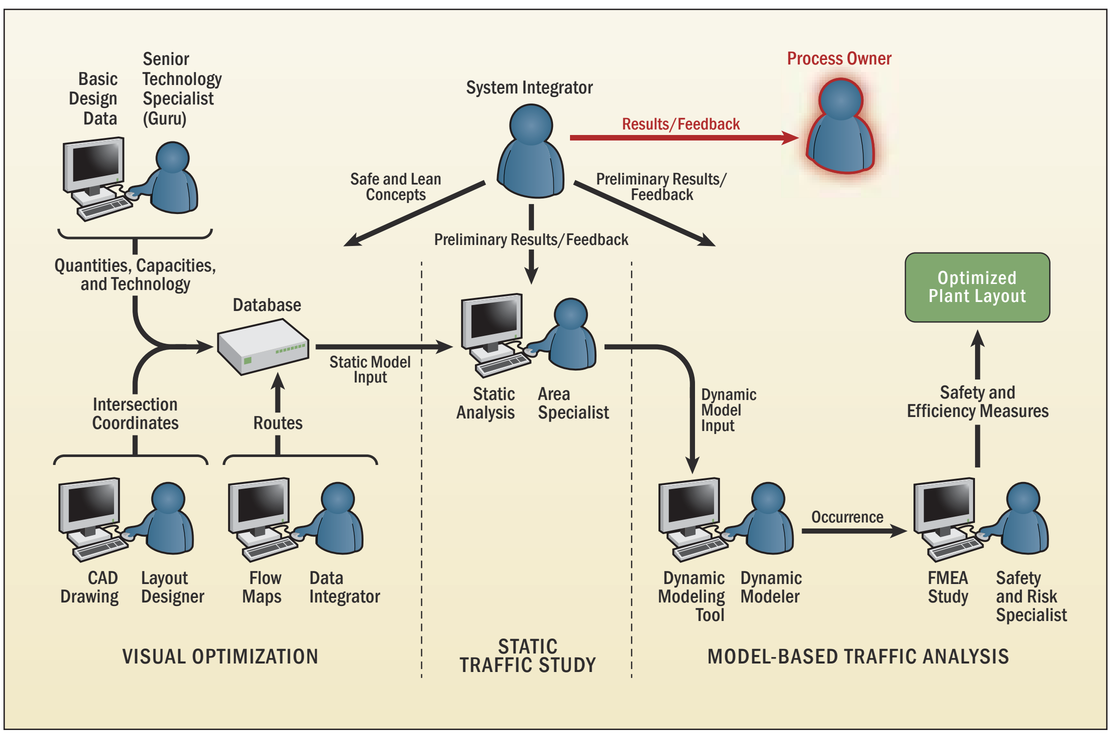

Figure 3. Integrated Approach to Plant Layout Development [1]

such as schedules and operational constraints. Emphasis is given to PPM movement (distance traveled per vehicle/person, intersection crossings, unsafe conditions, and possible bottlenecks on the road network).

The FMEA and CCF tools linked to the data set score the projected layout in terms of safety and efficiency. The main outputs of the platform are factors representing the risk of accidents in each specific intersection as well as an overall layout safety score, efficiency measures (cost, utilization of vehicles and load/unload stations, etc.), and CO_2e traffic-related emissions.

Additionally, the data set provides complete post-processing of the data simulated and collected. Some of the outputs include:

- Layout Safety Score: Average RPN from FMEA
- Layout Efficiency Score: Operating cost related to traffic
- Layout Emissions Score: CO_2e emissions related to traffic
- RPN of each intersection
- Number of vehicles required per flow type
- Distance driven per vehicle
- Number of trips executed per flow type
- Utilization of facilities (e.g., load/unload stations)
- Utilization of vehicles

Optimum benefits result from implementing the integrated approach early during project development.

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Figure 4 shows a sample of the overall score the platform generates for a layout once a few scenarios have been tested. A scenario represents any modification affecting the road network, such as plant arrangement, number of vehicles, schedules, routes, and number of stations.

CASE STUDY

Background

The integrated approach was applied to an aluminum complex consisting of an alumina refinery, an aluminum smelter, and an integrated rolling mill. The application focused on the interaction of smelter traffic with traffic from all facilities sharing the same external road network to nearby cities and ports. Understanding the traffic patterns was crucial to validating the operation of the aluminum complex.

Due to the sensitivity of the information about this project, the results presented in this paper for demonstration purposes are based on hypothetical data and a hypothetical plant configuration. These results focus on the approach used and the outcomes of the analyses.

Layout Analysis

The integrated approach was used to analyze the proposed layout. The key tasks [5] that the model was set to complete were:

- Identify the potential for traffic-related accidents
- Identify any bottlenecks impeding operational efficiency
- Validate the number of load/unload stations, lanes at the security gate, and weigh stations
- Validate the number of vehicles required

	SAFE	LEAN	GREEN
Scenario	Average RPN	Operating Cost (US$) for Transportation in 1 Week	CO_2e Emissions (tons) in 1 Year; Vehicles Owned by the Plant
Base Case	840	200,000	19,200
Scenario 1	510	190,000	19,200
Scenario 2	400	170,000	18,600
Scenario 3	850	210,000	19,800
Scenario 4	630	220,000	20,500
Scenario 5	420	210,000	20,400

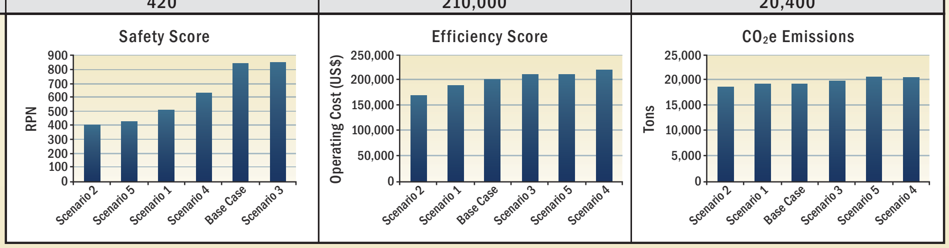

Figure 4. Overall Scoring (Sample)

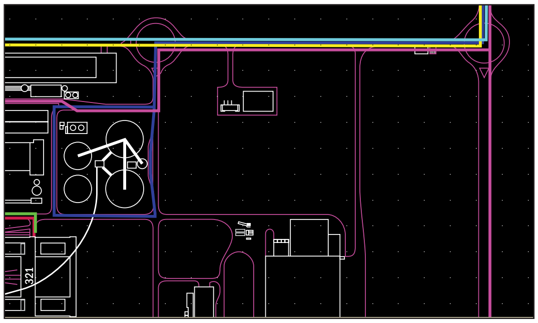

Figure 5. Mapping PPM Flow

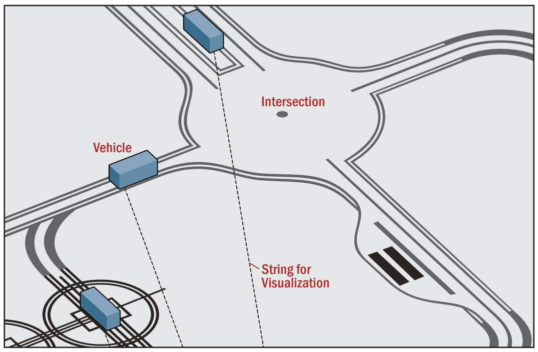

Figure 6. Example of Discrete-Event Model

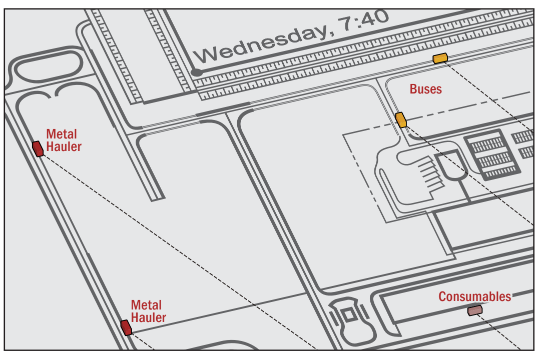

Figure 7. Smelter Model Snapshot

To cover this mandate, 1 week of simulated operation was targeted. The study was started by composing a list of flows expected during this typical week. Then, particular routes were defined and assigned to these flows. The platform automatically plotted PPM trajectories on the original CAD drawing, using multicolored lines (see **Figure 5**).

Knowing the PPM flow helped to align the project team (designers and future operators) regarding expected vehicle movement. By drawing attention to the mix of flows in any particular layout, PPM flow identifies potential areas of concern for analysis via the simulation. Eventually, it becomes the FMEA severity factor.

Once the team agreed on the list of flows and routes, the delivery schedule was defined for each flow. As part of the scheduling activity, operations such as metal tapping and anode change were executed in accordance with the expected potroom operational schedule. Annual requirements for each material were taken directly from the linked BDD model. The communication between the platform and the DEM shell was executed automatically. The discrete-event model was created from the input data with no user interaction required. Then, the simulation was performed and predicted output data recorded.

Figure 6 shows a typical vehicle intersection; to keep the focus on operational problems, visualization was kept to a minimum (e.g., colored boxes were used instead of 3D objects).

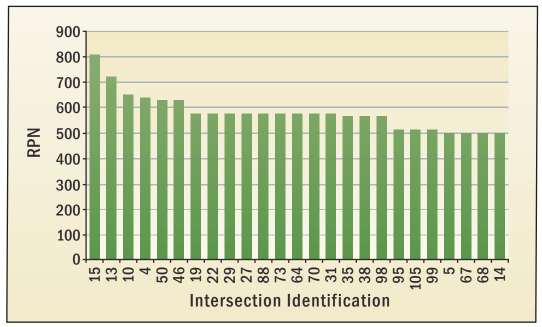

Figure 8. Safety—Intersection RPN Score

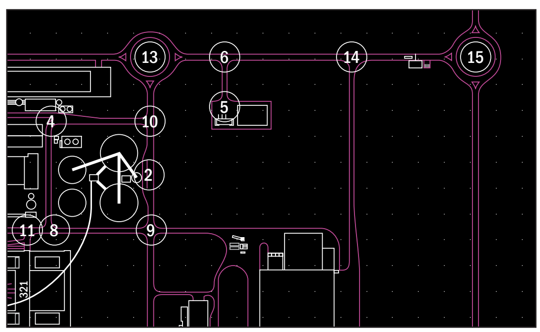

Figure 9. Intersection Identification

Figure 7 shows a snapshot of the smelter with various flows active. To bridge the size difference between the whole complex and the tiny vehicles, marker strings were used to visually locate the latter when the view was zoomed out.

Once the results were generated and post-processing was executed, an analysis followed to complete the key tasks listed above and to identify safety and efficiency issues.

Safety Results

Once the FMEA analysis was performed, an RPN was generated for each intersection; the highest score for each was presented in a Pareto chart. See **Figure 8** for the RPN values and **Figure 9** for the locations of the corresponding intersections.

The discrete-event model was created from the input data with no user interaction required. Then, the simulation was performed and predicted output data recorded.

As part of the validation process, a variety of scenarios were also run to understand the impact of an accident on the road.

The safety result is comparative and allowed the team to focus on intersections with the highest accident risk. In the case study, intersections 15, 13, and 10 scored the highest RPNs. For example, **Figure 10** presents the risk at intersection 15 over a period of time. The highest RPN score happens during shift change, when the frequency of crossings is significantly raised and cars and trucks interact.

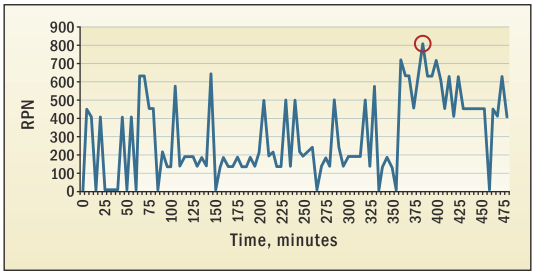

Figure 10. Intersection 15—RPN vs. Time

The following solutions were recommended:

- Intersections 15 and 13 required redesign, and truck deliveries were not allowed during shift change.
- Deliveries to the carbon plant were rerouted to avoid interferences with alumina deliveries at intersection 10.

Efficiency Results

The utilization analyses focused on the following aspects:

- Number of lanes at the gates
- Number of lanes on major roads
- Utilization of load/unload stations
- Utilization of truck weigh stations
- Utilization of casthouse TAC[2]/skim stations
- Operating cost related to traffic

The model validated the design of all load/unload stations, weigh stations, and security gates. **Figures 11 and 12** provide examples of the results generated by the model.

Figure 11 presents the utilization of the coke load/unload station during the 1-week simulation; predicted levels, including transient events, are within acceptable norms.

Figure 12 presents the utilization of security gate 1 by various delivery trucks during the

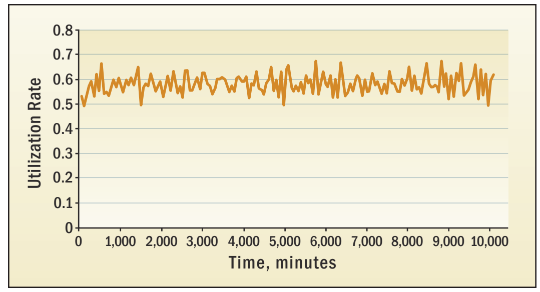

Figure 11. Coke Load/Unload Station Utilization

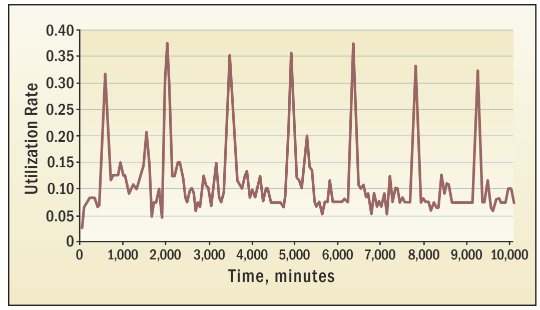

Figure 12. Security Gate 1 Utilization

1-week simulation. The peaks represent the highly concentrated day-shift deliveries; the model validated the number of lanes needed to inspect trucks. This example demonstrates the capabilities of DEM to predict peak performances.

As part of the validation process, a variety of scenarios were also run to understand the impact of an accident on the road between the port and the complex or the effect of a late ship arrival followed by a very early ship arrival.

Figure 13 presents the amount of alumina in a storage silo at the port during a 1-month simulation, assuming a late ship arrival followed by a very early ship arrival.

The blue line represents the results using *X* trucks, and the green line represents using *X + 1* trucks. After the arrival of the second shipment, the alumina trucks unload the silo as quickly as possible, and ship unloading is limited only by truck operation. In this case, one extra alumina truck provides the flexibility needed to efficiently

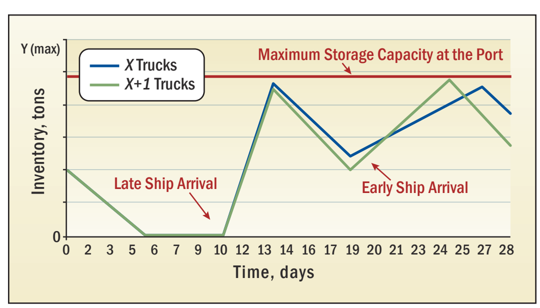

Figure 13. Hypothetical 1-Month Variation in Alumina Inventory at the Port

2 TAC stands for Treatment of Aluminum in Crucible, a process patented in the 1980s by Arvida Laboratories, Alcan International Limited, to eliminate lithium and other alkali metal contaminants from primary aluminum.

overcome the fluctuation caused by the second ship's early arrival. Thus, the extra truck reduces excessive demurrage costs.

POTENTIAL APPLICATIONS

ACE originally developed the integrated approach to support layout development activities for aluminum smelters and other traffic-intense facilities. However, a variety of operations could profit from the flexibility of this platform, including open pit mines, airport terminals, and construction logistics.

Open Pit Mines

The integrated approach could be used to optimize the material flow, resources, and crushed ore stockpiles of an open pit mine operation. For example, the platform could be applied to predict realistic truck arrivals and queuing at the crushing station. This realistic prediction of arrivals would help validate the crushing station design as well as the sizes of any intermediate stockpiles between the crushing and grinding stations.

Airport Terminals

During airport design, DEM tools have been used to analyze safety and efficiency aspects. The integrated platform would support mimicking the expected flow of passengers at an airport terminal. This analysis would provide certainty of outcome with respect to meeting International Air Transport Association (IATA) level of service (LOS) planning standards. Further, it would support analyses related to utilization of airport resources such as security scanners and customs.

Construction Logistics

The construction of large engineering projects usually involves a fair amount of material transport via trucks. The integrated approach could be used to predict the logistical impact of this massive flow on the access roads through a neighboring village. It could also enable the construction team to validate the inventory available at a particular time in the construction schedule.

CONCLUSIONS

Bechtel's ACE conceptualized, developed, and tested the integrated approach to developing safe and efficient plant layouts and then applied the platform to a particular project to validate the safety and efficiency of the proposed layout. This innovative platform delivered value by applying safety-by-design and waste elimination techniques. Early findings indicate that the integrated approach reduces the cycle time of aluminum smelter layout analyses by up to 50% compared to sequential, nonintegrated approaches.

The demonstrated flexibility of the integrated approach platform lends itself to a variety of applications on any project faced with evaluating traffic-intense operations during layout development activities. This new approach allows the quick comparative analysis of competing layouts to arrive at a safe, lean, and green plant configuration. ■

A variety of operations could profit from the flexibility of this platform, including open pit mines, airport terminals, and construction logistics.

TRADEMARKS

Flexsim is a registered trademark of Flexsim Software Products, Inc.

ACKNOWLEDGMENTS

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ADDITIONAL READING

Additional information sources used to develop this paper include:

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BIOGRAPHIES

Rafael L. Pires is a mechanical engineer for Bechtel's Mining & Metals Aluminum Center of Excellence. He provides expertise on multiple projects in the development of advanced simulations in areas such as material handling, resource optimization, operational schedule, and work design. Rafael's technical knowledge and skills have been applied to the Kitimat aluminum smelter (Canada), Ras Az Zawr aluminum smelter (Saudi Arabia), Ras Az Zawr integrated infrastructure project (Saudi Arabia), Quebrada Blanca copper concentrator (Chile), and Antamina copper-zinc concentrator (Peru), among others.

Rafael also assists on the application of safety by design and lean manufacturing techniques during the development of lean plant designs. He is currently supporting mechanical engineering analyses for various studies.

Rafael holds an MASc in Industrial Engineering from École Polytechnique de Montréal, Canada, and a BSc in Mechanical Engineering from Pontifical Catholic University of Rio de Janeiro, Brazil. He has authored/co-authored several technical papers, published by The Minerals, Metals & Materials Society (TMS), the *Journal of Aluminium Production and Processing*, and the Conference on Modelling and Simulation (MOSIM). Rafael is a licensed Engineer in Quebec, Canada, as well as in Brazil.

Robert F. Baxter is a technology manager and technical specialist for Bechtel's Mining and Metals Aluminum Center of Excellence. He provides expertise to the development of lean plant designs, materials handling, and environmental air emissions control systems for aluminum smelter development projects, as well as to smelter expansion and upgrade studies. He is currently one of Bechtel's technology leads for the Ras Az Zawr and Kitimat aluminum smelter studies.

Bob has 27 years of mining and metals experience, including 22 years in the aluminum electrolysis industry. He is a recognized specialist in smelter air emissions controls and alumina handling systems.

Before joining Bechtel, Bob was senior technical manager for Hoogovens Technical Services, where he was responsible for the technical development and execution of lump-sum, turnkey projects for the carbon and reduction areas of aluminum smelters.

Bob holds an MAppSc in the Management of Technology from the University of Waterloo in Ontario, Canada, and a BS in Mechanical Engineering from Lakehead University in Ontario, Canada.

Laszlo Tikasz, PhD, is the senior specialist for Bechtel's Mining & Metals Aluminum Center of Excellence. He has over 30 years of experience in advanced aluminum process modeling and is an expert on aluminum production and transformation, process modeling, and simulation. Laszlo has developed various process models and conducted studies to provide information needed to support engineering and managerial decisions on aluminum smelter designs, upgrades, and expansions.

Before joining Bechtel, Laszlo worked in applied research and industrial relations at the University of Quebec and an aluminum R&D center in Hungary.

Laszlo's PhD, in Metallurgical Engineering, is from the University of Miskolc, Hungary. His Doctor of Technology in Process Control and MSc degrees in Electrical Engineering as well as in Science Teaching are from the Technical University of Budapest, Hungary.

Robert I. McCulloch is the manager of Bechtel's Mining and Metals Aluminum Center of Excellence. He has global responsibility for aluminum smelter technology projects and studies, including reduction technology, carbon plants, casting facilities, and related infrastructure or systems. Bob is also responsible for the execution of aluminum industry projects and studies assigned to Bechtel's Montreal office.

Bob has over 41 years of experience in engineering and project management with Bechtel, primarily for projects in the mining and metals industries in Canada. His experience includes projects in the Canadian Arctic and management assignments in Montreal; Toronto; and Santiago, Chile. He recently returned to Canada after several years in Australia, where he led project management roles on two major projects.

Bob is a member of the Association of Professional Engineers of Ontario and was previously a member of the Canadian Standards Association Committee on Structural Steel and a corporate representative supporting the Center for Cold Oceans Research and Engineering in Newfoundland, Canada.

Bob holds a BEng in Civil Engineering from McGill University, Montreal, Quebec, Canada.