INTRODUCTION

Bechtel’s Aluminium Centre of Excellence (ACE) Knowledge Bank is the repository of the company’s institutional knowledge, technical capability, historical information, and lessons learnt on the design and construction of smelter projects. [1]

ACE applies efficient, highly valued, knowledge-based teams (headquartered in Montreal, Canada, but deployed to projects worldwide) to train, organise, and assign staff that enhance Bechtel’s ability to execute world-class primary aluminium industry projects.

To achieve excellence, ACE:

• Performs feasibility studies and leads development of project basic engineering for Bechtel primary aluminium projects globally
• Maintains a cadre of primary aluminium technology specialists to provide state-of-the-art knowledge and leadership to studies and technical support to projects
• Evaluates primary aluminium industry technology-based projects and products
• Develops and maintains relationships with primary aluminium industry leaders in technology supply, technical specialty, and technology-based equipment and systems supply

The primary objectives of ACE’s mandate to develop a simulation-based approach to validating lean plant configurations were to:

• Deliver certainty of outcome
• Make projects and operating plants lean, reliable, and cost-efficient
• Deliver value by applying simulation knowledge and skills to the configuration aspects of smelter projects

ACE used discrete element modeling of process elements to predict the dynamic response of the system to ensure that the proposed lean configuration can meet customer needs during normal, maximum, and upset operating conditions.
To drive off and burn volatile hydrocarbons and to improve the physical properties of the anode, green anodes are baked in a furnace at temperatures in excess of 1,000 °C (1,800 °F). The baked anodes are then rodded with electrical connections and transferred to the potline for consumption in the reduction process. Blending and creating usable prebaked anodes is a 2-week operation.

The challenges to achieving a lean, cost-efficient carbon plant configuration include:

- Capturing and articulating customer needs (as opposed to wants).
- Identifying and quantifying risks associated with driving a lean configuration, with proper regard for the system’s capability to be reliably operated and safely maintained.
- Demonstrating the capability of the proposed lean configuration to mitigate the identified risks and communicating the results to clearly address customer needs.
- Understanding and respecting industry experience and practices. With appropriate countermeasures, the lean configuration must convince the process owner that system stability, product quality, and ultimately the customer’s needs can be achieved over all operating conditions.
- Developing and validating the lean plant configuration early, during the project definition phase, and having a high certainty of the outcome. Design changes
A successful lean design begins by defining customer needs.

SIMULATION-BASED APPROACH—KEY ELEMENTS FOR SUCCESS

Understanding of Customer Needs

A successful lean design begins by defining customer needs under the following categories and task requirements:

- **Specify the Process Data**—Process data for the overall smelter and subsystems is captured and presented in the basic design data (BDD) mass balance model (see Figure 2). This model is a standard tool for capturing and presenting process data.
that ACE uses to coherently summarise and communicate key process data to the team. It also forms the basis for model validation. The example shown in Figure 2 is the BDD model used to define and summarise the key process data for the project that is the subject of this paper.

- **Develop and Document the Work Design**—A detailed understanding of how a system will be operated, maintained, and staffed, coupled with the desired organisational culture, is an essential input to the lean system design. The process of working with the process owner to develop and document the work design defines the critical customer and supplier interfaces and consumer needs. The flow of the value stream map created during this phase will later help determine where improvements are necessary.

- **Define Questions that the Model Must Answer**—With input from the process owner, concise questions that the dynamic model needs to answer are developed. The questions must be quantitative or binary so that the system’s capability can be determined. Questions should be based on the system’s capability to, for example, reliably deliver product, sustain inventory, or recover from a transient event.

- **Develop Key Metrics for Success**—Simple measures must be developed for each question to determine what output variable is to be measured and what the criteria are for acceptance or failure.

- **Construct Process Maps and Flow Charts**—These logic visualisation tools are used to capture the inputs resulting from the above activities and to analyze and discuss the process being evaluated (in this case, anode production and system maintenance). Constructing these maps and charts provides a solid foundation for the modeling phase, contributes to continuous process improvement, and is invaluable to the learning process. Ultimately, this step forces alignment between the process owner and the design engineer. It helps to close the information, data, and planning gaps that typically exist early in a project. An example of just one of the subsystems for moving anodes from the carbon plant to the potline is shown in **Figure 3**. [2, 3]

**Risk Assessment**

Failure mode and effect analysis (FMEA) is used to identify design and process risks associated with the proposed lean configuration and to quantify these risks in terms of their severity,
likelihood of occurrence, and detectability. This FMEA activity is performed with the process owner (the operations team in this case). Equipment and system reliability-based risks are entered into the models in the form of probabilities assigned to process units as mean time between failures (MTBF) and mean time to repair (MTTR) parameters.

Other risks associated with operator error and external factors are identified and quantified with the process owner and entered into the model as worst-case scenarios. Mitigating actions and countermeasures are then developed and applied to the models, and the results are evaluated with the process owner.

**Core Competencies**

Key core competencies required to analyze the system performance predicted by the model include:

- In-depth knowledge of a carbon plant’s subsystem technologies
- The overall system operational and maintenance requirements
- Knowledge of system break points, sensitivities, and limits

The ACE Knowledge Bank provides codified information captured from an extensive suite of aluminium smelter projects executed by Bechtel (and others). ACE specialists apply any available tacit knowledge and other relevant information to the initial analysis.

The development of countermeasures to mitigate the risks identified requires advanced simulation and modeling skills to understand cause-and-effect relationships and to identify a problem’s root cause.

All of these core competencies are essential to ensure the success of the overall modeling activity.

**ADVANCED PROCESS MODELING AND SIMULATION CAPABILITY**

Recently, process modeling and software simulation of systems have become integral parts of smelter studies and projects. As a result, an ever-growing, comprehensive model library has been developed and covers the main process sectors of an aluminium smelter. The models, which range from mass balance spreadsheets to discrete dynamic simulations, support sensitivity analyses and answer key questions regarding a system’s capability to meet customer needs.

Though extensive, the model library serves as a collection of building blocks with causes and effects that may guide the creator on building future models.

The modeling effort for each application must start with project-specific customer needs and inputs. More importantly, each model must be verified and validated before it is used as a predictive tool.

Verification, testing of model input parameters and boundary conditions, and validation of model dynamic outputs are essential steps in model development. A process owner’s confidence in model inputs and outputs is paramount for the owner’s acceptance of a proposed lean configuration. To achieve this desired outcome, model outputs are extensively tested against the BDD and known baseline performance from similar operating systems before the model is used to predict system performance.

**INTEGRATED MODEL-BASED LEAN PROCESS**

Combining the best of Six Sigma and lean manufacturing methods is an established and widely accepted improvement process. While Six Sigma reduces variation and shifts the mean to improve the output of a process, Lean focuses on the relentless pursuit of identifying and eliminating waste, which, from the end customer’s point of view, adds no value to a product or service. **Figure 4** lists Lean’s eight forms of waste.

Simulation tools complement and enhance improvement results by incorporating system...
Simulation tools complement and enhance improvement results by incorporating system reliability, variability, and risk into the design and optimisation process. Dynamic simulations also increase confidence that the proposed solution will deliver a lean, cost-efficient plant. These tools provide a cost-effective, flexible way to reduce and even eliminate scope changes and design variations in the proposed system beyond the project’s early definition phase. There are five steps to these software simulation exercises:

- **Define**—Characterise project scope, lean measures, structure, and variables
- **Measure**—Quantify current state, process model, and dynamic value-stream mapping (VSM); identify sources of variation and waste

Conceptualising, building, and validating the process model are linked to the Define and Measure phases of the Six Sigma process.

Applying the simulation tools intended to corroborate the outcomes of proposed improvements is done in the Analyze, Improve, and Control phases (see Figure 5).

**Figure 5. Model-Based Lean Approach (After El-Haik and Al-Aomar [4])**
An iterative tuning loop refines the system operating parameters that define the optimum design for the required inventories to be carried, the types and extents of countermeasures required, and the robustness of the proposed lean configuration.

MODELING AN IMPROVED CARBON AREA CONFIGURATION

Various simulation modeling tools can be used to validate carbon area configuration and operation. The two we used were:

• Anode baking furnace fire-train model (built and animated in a Microsoft® Excel® spreadsheet format)
• Carbon area operation, a discrete-event model (built using Flexsim™ dynamic simulation software from Flexsim Software Products [www.flexsim.com])

Anode Baking Furnace Fire-Train Logic Validation—Excel-Based Model

We dynamically analyzed the operating sequence, fire configuration, cycle times, fire movements, and empty pit locations for an anode baking furnace. The objective was to determine if a simulated group of sufficiently cooled, empty pits could be made available for an extended period so that maintenance and repair activities could be performed safely.

To address the issue, we created an Excel spreadsheet model built with simple interfaces and integrated detailed operating logic (see Figure 6). We kept all main process parameters adjustable (for example, definition of a fire train, fire move direction, location of burners and bridges, required baking time, and initial positions).

By simulating several months of operation, the model helped us to develop and debug the operational logic. Once the simulated model verification and validation testing was completed, we transferred the operational logic to the more detailed dynamic discrete event model for the anode baking furnace.

Combined Anode Plant Facilities

We built a dynamic simulation model of the anode plant facilities to validate the basic operating
The objective of the modeling effort was to identify potential fatal flaws, system weak links, and other conditions that could interrupt or delay the process.

Capability of our proposed lean configuration (see Figure 7). The objective of the modeling effort was to identify potential fatal flaws, system weak links, and other operational conditions that could interrupt or delay the process of delivering baked anodes to the rodding shop and rodded anodes to the potroom, or that could render the system unable to recover from potential transient events in the paste plant, baking furnace, or rodding shop. We designed the model to answer the following core plant safety, design, and operation questions:

- Could the proposed anode supply system sustain normal potroom operation without interruption?
- Does the proposed storage capability (combined indoor and outdoor) of green and baked anodes support the baking furnace and paste plant operating and maintenance plans as specified in the BDD?
- Could a single automated stacker crane reliably manage the inventory for a common green and baked anode storage facility?
- Could the proposed system recover from a transient event within reasonable time to sustain the potroom demand for carbon without depleting the rodded anode inventory in the pallet storage area?
- Does the rodded anode buffer (pallet storage area) between the reduction area and the rodding shop have sufficient capability to ensure that cooled product was available to sustain the scheduled rodding shop operations?
- Is the system capable of sustaining the carbon supply operation over the long term when equipment reliability and system availability are considered? We identified what, if any, weak links existed.

We designed the model to simulate the production and subsequent handling and storage of green anodes up to the anode baking furnace. The model also simulated the handling and storage of anodes from the baking furnace to the anode rodding shop and then on to the pallet storage area before their removal for use in the potrooms.

Since the anode baking furnace operation had been previously modeled and proven using other software tools, we incorporated only the summary logic for green anode consumption and baked anode production into the discrete-event software simulation model.

Metrics for Success

We used the following metrics to determine whether the core plant safety, design, and operation questions had been correctly and accurately answered and whether the proposed optimised configuration was suitable for the project:

- Feed potroom based on "pull" (i.e., demand); do not interrupt pot-tending activity
- Maintain minimum anode inventory for normal operation, with short, minor dips below 10% during random breakdowns (8 hours for either green or baked anodes) in the anode storage facility
• Do not deplete rodded anode inventory in the pallet storage area during critical events
• Demonstrate the system’s capability to recover within a specified period without disrupting production in the potroom or rodding shop

Model Inputs
Model inputs included the following information:

• The work design (working and down periods) applied to the paste plant, anode baking furnace, rodding shop, and potlines as defined in the project BDD
• Preventive maintenance schedules applied to all components of the anode handling system (conveyors, accumulating conveyors, elevators, stacker crane, pushers, anode tilters, anode turners, and turn tables) as defined by the project BDD
• Component breakdowns captured and implemented by MTBF and MTTR, as driven by random functions and based on historical data

Model Granularity
Addressing the whole carbon area, we set the model granularity in accordance with the particular interest in the sector studied. We also used modeling blocks and complete sector models with different granularities; for example:

- Green and baked anode storage was an area that presented significant optimisation opportunity; thus, all major components (stacker crane, conveyors, elevators, rotating units, anode blocks, and other outputs) were modeled individually (see Figure 8).
- When the cold butt and pallet inventories were monitored, a simple, pallet-based representation of anodes was applied. Color codes marked the status (red = hot butt, yellow = cold butt) and pallet type (grey = rodded anodes) (see Figure 9).

Model Simulation Validation
Before the model was used to run any production scenarios, it was fully validated using data from the BDD.
using data from the BDD. To improve the certainty of model predictions, we also parametrically checked predicted outputs against the ACE Knowledge Bank.

We tested each section of the model (paste plant and anode cooling, anode storage and handling, anode baking furnace, rodding shop, and pallet storage) individually with inputs from the BDD and constants for availability and reliability. Using these known data inputs, we were able to modify and debug each section until it reliably produced the predicted outputs and mass balance.

After all sections were tested, we reintegrated the model and then tested it again under known conditions in order to:

• Test the handshakes between the various sections
• Verify that repeatable results could be obtained against known outputs

Finally, we made a full model run to simulate a year of production, with all data per the BDD. We then compared the outputs over this time period with the predicted 1-year values in the BDD. We introduced reliability and statistical variability into the model runs only after the model was fully tested.

Effect of Transient Events in Rodding Shop
In selected model runs, we introduced transient events into the model. For example, we simulated an extended shutdown of the rodding shop.

The normal scheduled rodding shop maintenance shift is 8 hours. To test restart problems, we increased the restart time by 8 hours, 16 hours, and 24 hours. As a worst-case scenario, we shut down the rodding shop for 32 straight hours (8 scheduled plus 24 unscheduled).

Next, we observed the impacts on the pallet storage area and the green and baked anode storage area (see Figures 10 and 11, respectively). During these transient events, the green and baked anode storage area was able to accommodate the storage of baked anodes that could not be sent to the rodding shop, without affecting baking furnace production.

From these model runs, we concluded that reasonable transient events within the rodding shop have no effect on potroom production.

Countermeasures
To manage the planned long-term system interruptions that would be needed to perform certain proposed actions—a reduction of the covered storage building area, a reduction of inventory costs, and the elimination of the second stacking crane—we developed countermeasures that included scope changes or actions such as:

• Developing a planned outdoor green anode storage area to accommodate the paste plant’s annual shutdown
• Allocating identified critical spare parts on site
• Taking steps to increase equipment reliability and reduce MTTR
• Configuring the equipment so that handling, storage, and conveyance operations could be performed manually

![Figure 10. Changes in Pallet Storage Area Capacity](image)
To investigate the availability of existing countermeasures outside the plant (and possibly the company) for emergencies having a low probability of occurrence but a high severity, we elevated risk to a corporate level. This assessment included considering countermeasures such as supplying anodes from sister plants or from outside suppliers.

Results

Based on the proposed aluminium smelter plant design, the dynamic model results predicted that all defined metrics for success could be met.

- **Benefits**—The benefits of adopting a validated lean carbon plant configuration—compared with using conventional designs—to handle, store, and convey green, baked, and rodded anodes include:
  - Significant reductions in green and baked anode inventories
  - An anode storage configuration sharing a common area for green and baked anodes and serviced by one stacker crane
  - Reduced conveyor lengths and handling operations so that customer and supplier connections are direct and short
  - Reduced maintenance costs as a result of simplifying and reducing the handling and conveyance equipment

- **Projected Cost Savings**—Based on the data generated by the study team, the cost savings that would be realised by using the proposed optimised lean anode storage facility, as validated by the discrete event modeling methodology described in this paper, would be approximately US$2 million in capital cost savings and US$400 thousand in operating cost savings (expressed in terms of present value).

- **Recommendation**—We recommend that the proposed lean carbon plant configuration, along with the identified countermeasures, be implemented for the aluminium smelter project.

CONCLUSIONS

Integrating simulation-based tools with Lean and Six Sigma quality improvement methods is an effective approach to validating and improving lean configurations; indeed, with owners expressing the need for competitive life-cycle costs, simulation may be considered an essential design component.

For the lean carbon plant configuration discussed in this paper, simulation submodels of the facilities used for anode fabrication, anode storage, anode baking, rodding, and pallet storage were linked by an overall anode handling, storage, and conveyance system model. Model inputs involved a rigorous approach to defining customer needs, including process design, work flow, and waste elimination (redundant material handling equipment and storage capacity, for example).

To implement our simulation-based approach to validating the lean carbon plant configuration, we used the following general methodology:

- Scenarios were performed under projected normal, transient, and extreme operating conditions.
- Reliability and other risks were applied as worst-case scenarios.
• The system dynamic response was recorded.
• Findings were fed back to designers and process owners and then analyzed against the lean design criteria.

Our advanced simulation and 3D modeling methods and tools enabled us to create, develop, test, and validate a sequence of operations that add value to the customer with the least amount of waste. We targeted and achieved reduced storage space; a single anode stacker crane; and appropriate green, baked, and rodded anode inventories. We further demonstrated that adequate inventories could be achieved under all operating, maintenance, and transient operating conditions for the proposed lean carbon plant configuration.

In any simulation effort, it is essential to follow the key elements for success identified near the beginning of this paper, to ensure that:

• Customer needs are fully defined and captured in a manner that can be transferred into the simulation model and measured against defined metrics for success.
• Reliability, operational risks, and worst-case scenarios are identified and quantified for the proposed system.
• The simulation software model is fully verified and validated before it is used as a predictive tool. This is an essential step for acceptance of the proposed lean configuration.

An in-depth knowledge of subsystem technologies; overall system operational and maintenance requirements; and system break points, sensitivities, and limits is critical to the modeling success. These core competencies must be applied throughout the simulation model development, testing, and output analysis.

A simulation-based approach delivers confidence to the process owners and project team that:

• The proposed solution will meet or exceed expectations.
• Uncertainties have been defined and mitigated.
• Value can be delivered in the form of scope reductions, scope stability during project execution, and reliable startup and operational performance.
• Alignment with the process owner is maintained at each step to ensure that customer needs are understood, captured, and integrated.

A substantial productivity and cost-savings benefit of this early and ongoing collaboration is that it can reveal lessons learnt that may not otherwise be readily evident. Typically, these lessons remain overlooked until they are rediscovered after the plant is built. Such collaboration is a learning process by itself and serves as a solid foundation for the modeling phase. Thereby, it builds confidence in the model results.

Taking the holistic approach presented in this paper to developing and validating a lean, cost-efficient configuration early enough in the project development cycle results in significantly added value, including:

• Reduced waste
• Lower capital and operating costs
• Improved productivity
• Assured reliability
• Certainty of outcome
• Alignment with customer needs

TRADEMARKS

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REFERENCES


Robert Baxter is a technology manager and technical specialist in Bechtel's Mining & Metals Aluminium Centre of Excellence in Montreal, Canada. He provides expertise in the development of lean plant designs, materials handling, and environmental air emission control systems for aluminum smelter development projects, as well as in smelter expansion and upgrade studies. Bob is one of Bechtel's technology leads for the Ras Az Zawr, Massena, and Kitimat aluminum smelter studies.

Bob has 26 years of experience in the mining and metals industry, including 20 years of experience in aluminum electrolysis. He is a recognized specialist in smelter air emission 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 Management of Technology from the University of Waterloo and a BS in Mechanical Engineering from Lakehead University, both in Ontario, Canada, and is a licensed Professional Engineer in that province.

Trevor Bouk is a technical specialist in Bechtel's Mining & Metals Aluminium Centre of Excellence in Montreal, Canada, with 17 years of experience in the mining and metals industry. He is currently the carbon area specialist providing technical and process expertise for the development of the carbon facilities required to support the aluminum electrolysis process. Trevor provides support for aluminum smelter development studies and projects.

In addition, Trevor has also performed lead roles on multiple projects. Most recently, he was the carbon lead on the Ras Az Zawr aluminum smelter FEED study and the lead carbon area engineer on the Fjarðaál project in Iceland, where he was responsible for the overall design and layout of the carbon facilities as well as involved with the onsite construction and startup. Trevor also provided technical and process troubleshooting services to operating smelters.

Before joining Bechtel, Trevor was involved with the design and supply of automated process equipment to the aluminum industry, both in anode rodding shops and casthouses. He also supported the installation, startup, and early operation of many jobs, ranging from single machines at existing plants to multiple systems on large greenfield projects.

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Laszlo Tikasz, PhD, is the senior specialist for Bechtel's Mining & Metals Aluminium Centre of Excellence in Montreal, Canada. He has 29 years of experience in advanced aluminum process modeling and is an expert on aluminum production and transformation, process modeling, and simulation. Laszlo has developed flexible process models and studies to provide information needed to support engineering and managerial decisions on aluminum smelter designs, upgrades, and expansions.

Before joining Bechtel, Laszlo worked in research and industrial relations at the University of Quebec and the Hungarian Aluminium R&D Center.

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Robert I. McCulloch is manager of Bechtel's Mining & Metals Aluminium Centre of Excellence in Montreal, Canada. 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 40 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 had lead project management roles on two major projects.

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