PORT AND RAIL INFRASTRUCTURE EXPANSION PLANNING AT ARCELORMITTAL MINES CANADA VIA DYNAMIC COMPUTER SIMULATION[1]

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Abstract

A dynamic computer simulation model was developed for the purpose of determining the capital investments and operational changes that would be required in port and rail to support iron ore production increases. The model considered the logistics involved with handling, storing and transporting iron ore, pellets and various raw materials. The discrete-event dynamic simulation model, based on ARENA, was validated against a historical period of one year. The validation established (1) confidence that the model properly replicated the real operation and (2) a baseline from which to compare future scenarios. The model was then used to conduct what-if analyses to debottleneck operations, compare alternatives and optimize the overall expansion plan in terms of logistical capability, capital effectiveness, operational efficiency and timing of investments and operational changes. Requirements for rolling stock inventories, track layouts, rail service schedules, stockpile and silo capacities, number of shiploaders and loading rates, number of berths, and number of railcar dumpers for each phase of the expansion were determined. The dynamic nature of simulation allowed for a realistic assessment of proposed future operations.

Key words: Simulation; Logistics; Port and rail infrastructure; Iron ore mining; Pellet.

PLANEJAMENTO DA EXPANSÃO EM INFRAESTRUTURA PORTUÁRIA E FERROVIÁRIA EM MINAS DA ARCELORMITTAL NO CANADÁ VIA SIMULAÇÃO DINÂMICA COMPUTACIONAL

Resumo

Um modelo de simulação dinâmica foi desenvolvido com o propósito de determinar o investimento e mudanças de operacionais necessárias em portos e ferrovias para suportar aumentos de produção de minério de ferro. O modelo considerou a logística inerente ao manuseio, armazenagem e transporte de minério de ferro, pelotas e várias outras matérias primas. O modelo de simulação dinâmica de eventos discretos, baseado em Arena, foi validado sob um período histórico no ano. A validação estabeleceu (1) confiança que o modelo replica apropriadamente a operação real e (2) uma base a partir da qual comparam-se cenários futuros. O modelo foi então usado para conduzir analises hipotéticas para retirada de gargalos de operação, comparar alternativas e otimizar o plano de expansão geral em termos de capacidade de logística, efetividade de investimento de capital, eficiência operacional, tempo de investimentos e mudanças operacionais. A simulação permitiu que fossem determinados os requisitos para inventários, "layouts", serviços ferroviários, capacidades de pilhas e silos, número de "shiploaders", taxas de carregamento, número de berços e números de basculadores para cada fase de expansão. A natureza dinâmica da simulação permitiu análise realística de cenários futuros.

Palavras-chave: Simulação; Logística; Infraestrutura portuária e ferroviária; Minério de ferro; Pelota.

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1 INTRODUCTION

1.1 Background

ArcelorMittal Mines Canada presently operates the Mt-Wright mine and concentration complex in the northern Quebec region, pelletizing and port facilities in Port Cartier, and a wholly-owned railway linking the two sites. In 2008, a company-wide expansion project was initiated which studied the possibility of expanding the present facilities and the opening of new mine sites. The simulation work was part of a prefeasibility study to upgrade railroad and port infrastructure in order to accommodate the increased transport requirements of the expansion. This paper focuses on the simulation component of the prefeasibility study and how simulation was used to assist in defining the overall railroad and port capital expansion program.

1.2 Objectives

The objectives of the prefeasibility study included:

- Assessment of the capabilities of current rail and port operations and determination of their maximum capacities;
- Identification of bottlenecks at each expansion step;
- Determination of rail and port investments and operating strategies to support the capacity expansion program at each expansion step;
- Optimization of the overall capital investment plan to achieve the proposed maximum capacity;
- Estimation of the overall capital cost to +/- 25%.

Simulation played an important role in achieving each of these objectives by quantifying performance metrics, by providing the means for devising debottlenecking strategies, and through assessing the impact of capital investments and operational changes on overall system performance.

1.3 Approach to Work

The overall study encompassed a railroad expansion study, a port expansion study, and a logistics dynamic simulation study. The three components were carried out in parallel and were closely linked to ensure that global, integrated solutions were achieved. The synthesis of the studies resulted in an overall capital investment program that defined the necessity, timing, and estimated costs of capital investments and operational changes to achieve the maximum targeted “pit to port” capacity.

The railroad and port expansion studies each focused on:

- Assessment of current operations and capabilities;
- Determination of practical approaches and possibilities to achieve targeted capacities;
- Development of a plan for achieving targeted capacities.

The logistics simulation study focused on:

- Quantification of the maximum capacity of the integrated supply chain (“pit to port”) for the current operation, for each phase of the expansion, and for each what-if scenario within each expansion phase;
- Identification of bottlenecks at the current production volume and at each expansion volume;
- Determination of threshold values at which resources become constrained;

- Evaluation of the solutions to achieve increased capacities as determined by the railroad and port studies;
- Optimization of the capital investment plan via what-if and sensitivity analyses (optimal combination of number of berths, loading/unloading rates, rolling stock inventories, vessel fleets, etc. for each capacity step).

1.4 Simulation Rationale

Understanding that systems must be optimized in their totality, the simulation methodology considered the “pit to port” operation as an integrated system and not as isolated subsystems. It explicitly accounted for the elements of:

- Time;
- Variability;
- Interferences and interactions between and within subsystems;
- Random events, e.g. equipment failures and weather delays;
- Operational constraints, such as vessel draft requirements.

This allowed capacity losses due to these factors to be accurately quantified. Once the simulation model was built, what-if analyses were easily carried out to:

- Evaluate and compare alternatives;
- Understand bottleneck dynamics;
- Identify potential design flaws;
- Develop solutions/strategies for managing constraints;
- Optimize performance.

For these reasons, dynamic simulation provided a powerful means of practically, realistically, and accurately assessing future operating performance. It is a proven methodology that has been in continuous use since the early 1960’s, particularly by capital-intensive industries such as the iron and steel industry, to help (1) get designs right the first time and avoid big mistakes, (2) ensure operational robustness and the achievement of capacity targets, and (3) ensure capital effectiveness and operational efficiency.

Static means of analyses, such as spreadsheet models or linear programs, generally fail to capture the full impact of dynamic disturbances on operational performance. For example, static models generally fail to capture the full effects of random equipment failures and logistical interferences as they arise and propagate through a system. Consequently, static models tend to overestimate system capacity and generally lack the dynamic characteristics and structural soundness that are necessary to properly extrapolate future performance.

2 SIMULATION METHODOLOGY

One of the keys to a successful simulation study is to follow a comprehensive life cycle in an organized and well-managed manner. Each of the activities comprising the general simulation life cycle, as applied in this case study, are described in this section. Many of the activities related to the life cycle may be repeated a number of times, and do not necessarily follow each other in sequential order. This is due to the iterative nature of modeling in which an understanding of system behavior tends to deepen as new insights are revealed via what-if analyses, which leads to further experimentation and analysis in search of an optimal solution.

2.1 Problem Formulation

Problem formulation involved translating the communicated problem into a formulated problem that was sufficiently well defined to enable a specific study. Once the problem was defined, the proper method to employ for solving it was determined. As explained in Section 1.4, simulation was determined to be the proper method to employ in defining a capital expansion program to support future production volumes.

2.2 Project Planning

Project planning involved specifying the particular questions to be answered by the model, establishing model breadth and depth, identifying constraints involving schedule, budget, and resources, and establishing decision-maker expectations. It was critical to define the specific questions to be answered by the model because the model was built around answering these questions. The nature of the questions governed the degree of model scope and model detail. Some of the questions to be answered regarding the railroad included:

- How much rolling stock inventory is required?
- What are the track layout requirements?
- What are the train service requirements?
- What are the train loading and unloading rate requirements?
- What silo capacities are required?
- How much track maintenance can be done before causing serious disruptions to operations?
- What modifications to rail traffic control rules are required?

Some of the questions to be answered regarding the port included:

- What are the berth requirements?
- Is dredging required?
- What loading and unloading rates are required?
- What stockpile capacities are required?

Based on these questions, appropriate model boundaries, assumptions, simplifications, and exclusions (to keep the model as simple as possible without sacrificing the quality of model results) were established by the project team, which worked closely together throughout the course of the study. The team was comprised of members, from both ArcelorMittal and Hatch, with expertise in the areas of port operations, rail operations, iron ore processing, material handling, logistics, modeling and simulation, and project management. This set of skills was essential in enabling the model to be properly conceptualized, validated, experimented with, and trusted to assist with major capital investment decisions.

2.3 System Definition and Synthesis

In order to properly model a system, the system must be properly understood. To this end, workshops were held with key operating personnel (from both rail and port operations) to (1) define the system, (2) identify the critical components that needed to be modeled very carefully, (3) discuss potential solutions for debottlenecking current operations and increasing capacities, and (4) define primary model inputs, outputs, operational constraints, philosophy, and operating rules.

The current port is comprised of an approach channel, turning basin, inner harbor, six berths, a shiploader, and a stockyard with commodity stockpiles, stacker-reclaimers, rail dumpers, and conveyors. Figure 1 shows an aerial view of the port. The channel is dredged to 54.5 feet at mean low tide and the inner harbor is dredged to 50 feet at mean low tide. Cape size vessels are subject to draft restrictions and must wait for a high tide that will provide sufficient time to sail out on. Two tug boats are available to assist with vessel berthing, deberthing, and channel navigation. Only one vessel can navigate the channel at a time. Export commodities include iron ore pellets, iron ore concentrate, and grain. Import commodities include bentonite, limestone, dolomite, coke breeze, and petroleum. Commodities are assigned particular berths for loading/unloading and there are constraints that limit the number of certain combinations of different class vessels that can be in the inner harbor simultaneously. The port is subject to weather delays that may cause loading and unloading operations to stop. Stacker-reclaimers are used to stack and reclaim iron ore pellets and iron ore concentrate from stockpiles. Conveyors are used to move materials that are being stacked or are being reclaimed between the stockpiles and either the pellet plant or ship loader. The general vessel cycle is defined as follows:

- Arrive to port, queue for the specified berth, prepare paperwork;
- Wait for tugs, pilot, and channel to become available;
- Navigate channel and berth vessel;
- Load or unload vessel;
- Wait for a sailing window of opportunity;
- Wait for tugs, pilot, and channel to become available;
- Deberth vessel and navigate channel;
- Depart port.

Figure 1: Aerial view of Port Cartier.

The current railroad is comprised of a single, main line track that is 260 miles long between Port Cartier and Mt-Wright and has 19 sidings and 3 junctions. One of the sidings has a nearby camp site to accommodate crew changes. Train service includes consists for transporting raw iron ore, iron ore concentrate, wood, freight, and passengers. Rail traffic control rules are used to dispatch trains onto the main line and safely advance them along the rail network until they reach their final destination. Constraints involving track maintenance, locomotive and railcar failures, weather conditions, crew changes, and railroad regulations are important characteristics that must be considered in managing rail operations.

2.4 Model Definition and Formulation

Model definition and formulation involved designing a conceptual model that captured the essence of the real system in a way that neither oversimplified the system to the point where the model became trivial, nor carried so much detail that it became expensive to build and run. One of the reasons for having a multi-disciplined expert project team is so that a proper conceptual model can be formulated. As previously discussed, railroad and port operations were the primary components that needed to be considered in the simulation model. Some of the primary model assumptions, simplifications, and exclusions included:

- Assuming manpower was available as needed;
- Modeling the concentrators as "black boxes" that produced iron ore concentrate at historical hourly production rates;
- Modeling the pellet plants as "black boxes" that consumed iron ore concentrate from the concentrate stockpile and produced iron ore pellets at historical hourly production rates;
- Assuming all ship queuing was based on a first-in-first-out queue discipline, except for draft restricted vessels, which were given highest priority when ready to deberth;
- Stacker-reclaimers and port stockyard conveyors were not explicitly modeled. Shiploading delays due to stacker-reclaimer delays were incorporated into shiploader operational delay parameters.

Primary model inputs and outputs are summarized in the following table.

Table 1: Primary model inputs and outputs

Component	Port	Rail
Inputs	• Vessel arrival rates • Vessel loads • Shiploading delay frequencies and durations (operational, mechanical, electrical) • Hourly tide height • Vessel draft requirements • Loading and unloading rates • Weather delay frequencies and durations • Channel navigation durations • Berthing durations • Stockpile capacities	• Train service schedules • Rolling stock inventories • Railcar and locomotive availabilities • Train travel durations between stations in the northbound and southbound directions • Loading and unloading rates • Crew change durations • Track delay frequencies and durations • Silo capacities
Outputs	• Import and export volumes • Ship time at port • Ship time at berth • Berth utilization • Shiploader utilization • Stockpile inventory profiles	• Train cycle • Locomotive cycle • Silo inventory profiles

The dynamic model structure was built using algorithms and rules of logic that were capable of dealing with day-to-day disruptions and system interactions that are typically encountered in actual operations. For example, a rail traffic control algorithm was developed to manage the meeting of trains so as to avoid collisions. Another algorithm was developed to find sailing windows of opportunity for draft restricted vessels. Rules for dealing with unplanned equipment failures, weather delays, and scheduled track maintenance were developed to minimize capacity losses during upset conditions and return operations to steady state as quickly as possible. These are some of the rules and algorithms that formed the dynamic system structure of the model and were critical in properly evaluating future scenarios.

2.5 Input Data Analysis and Modeling

Upon defining the conceptual model, all input parameters were defined. They were then collected, analyzed, and prepared for use in the simulation. Primary sources of input data included production, port, and railroad databases, estimates from system experts, and product mix forecasts from marketing. Data downloaded from databases was carefully reviewed to ensure data was used properly and that double counting of items did not occur. For example, in preparing input distributions for equipment process times, it was important to distinguish queue time from processing time. It was not sufficient to look at an arrival time and a departure time. This is because queue time is actually a model output, not an input, since queue time is a function of system dynamics. After the data was analyzed, statistical input distributions were defined as well as probabilities involving random equipment failures and weather delays. Many of the model inputs were variable and were represented in the model by empirical distributions. It was crucially important that input data analysis and modeling were carefully conducted since a model can only be as good as the input that goes into it.

2.6 Documentation and Review of Model Functional Specification

After the model design was completed, a functional specification document was drafted that explicitly defined the purpose and scope of the simulation model, as well as the operating logic and parameters that formed its basis. The document was issued to all stakeholders seeking approval to proceed with programming. This approval helped to avoid major reprogramming efforts later on.

2.7 Model Translation

Once the functional specification was approved, the process of translating the conceptual model into a computer program began. The software used to develop the computer simulation model was Arena, which is a general-purpose discrete-event simulation package. It is a product of Rockwell Software that combines a simulation programming language, SIMAN, with an animation package, CINEMA, and an embedded procedural language, Visual Basic for Applications, VBA. The simulation model was built from scratch using Arena. A custom user interface in Excel was developed and VBA was used to communicate between Arena and Excel for both input and output communication.

2.8 Verification and Validation

Model verification involved ensuring that the model behaved as the programmer intended it to behave. It was an integral component of model translation that occured continuously throughout the entire computer programming process. Model validation involved ensuring that the model sufficiently represented the true system of interest, not only in the reproduction of performance metrics, but also in the manner in which those metrics were reproduced. In other words, validation ensured that the dynamic model structure closely matched the internal workings of the real system to reproduce real system behavior. The validated model established confidence that it could be used to accurately predict future performance, and provide a point of reference for comparison of options. A validation period of one full year was chosen in order to capture seasonal affects, such as ships not having access to nearby waterways during winter months. The primary parameters that the model was validated against included stockpile inventories, vessel time at port, and train cycles.

2.9 Experimentation and Analysis

Upon successful completion of model validation, experiments were designed to test what-if scenarios and perform sensitivity analyses to debottleneck operations, evaluate and compare alternatives, and optimize the overall expansion plan. Some of the experimental factors considered are shown in Table 2.

Table 2: Simulation experimental parameters

Rail Parameters	Port Parameters
• Number of railcars per train • Number of locomotives per train • Number of consists in service • Railcar axle load capacities • Use of dedicated yard locomotives • Crew change durations • Track maintenance schedules • Minimum train dispatch interval duration • Silo capacities • Track layout	• Shiploader capacities • Number of shiploaders • Berth assignments • Ship loading constraints

Analysis generally involved studying both the dynamic and aggregate behavior of the system. Dynamic performance was studied by looking at plots of relevant simulation variables as they changed over time. Aggregate performance was studied by looking at statistical analyses of simulation-generated data such as means, variances, minima, maxima, and histograms. Scenarios were iteratively defined, simulated, and analyzed until solutions were reached. Sensitive parameters were identified and evaluated over a range of values. Since the model contained variable input parameters, it generated variable outputs. Consequently, multiple simulation replications were executed for each scenario to understand the variability in model outputs. A discussion of model results can be found in Section 3.

2.10 Communication, Documentation, and Implementation

Simulation results were used to assist in defining the capital expansion program scope and enabled estimation of capital costs. The capital expansion program was documented and presented to executive management in September 2008. Following the economic crisis of Q4 2008, the expansion project was put on hold.

3 RESULTS AND DISCUSSION

3.1 Debottlenecking Philosophy

What-if experimentation was conducted to better understand and quantify current bottlenecks, test and evaluate debottlenecking strategies, and quantify the combined benefits of various combinations of capital investments and operational changes at each targeted volume of the expansion plan. The general philosophy used in search of an optimal solution was based on minimizing capacity losses due to interferences and making up any capacity deficits relative to targets by increasing operational redundancy and/or increasing operational rates. In other words, debottlenecking and optimizing current operations and investing capital to make up for any shortfalls relative to expansion targets. The criteria for a viable solution was based on meeting shipment volume targets, minimizing capital investment, minimizing upward deviation from the *current average vessel time at port* statistic, minimizing upward deviation from the *current average train cycle* statistic, and maximizing operational flexibility.

3.2 Debottlenecking Example

Since port and railroad operations can essentially be decoupled by ensuring that the commodity stockpiles are large enough to minimize disruptions to each others' operations, one of the objectives of the model was to find a way to move material in a timely manner to minimize such disruptions while at the same time minimizing capital investments. Regarding rail operations, it was particularly important to transport iron ore concentrate to the port stockyard via rail in a timely manner so as to avoid pellet plant starvation. Regarding port operations, it was particularly important to service ships in a timely manner so as to avoid major demurrage penalties.
The first step in the debottlenecking process was to identify the constraints that prevented the objective function from being achieved. A simulation scenario tested under the current configuration with a product mix for the first phase of the expansion identified iron ore concentrate rail service as the first system bottleneck. Figure 2 shows that the current rolling stock inventory for this scenario was inadequate. Even with an initial stockpile level almost three times greater than the maximum actually experienced, inventory was depleted, essentially idling pellet production and consequently shipments.

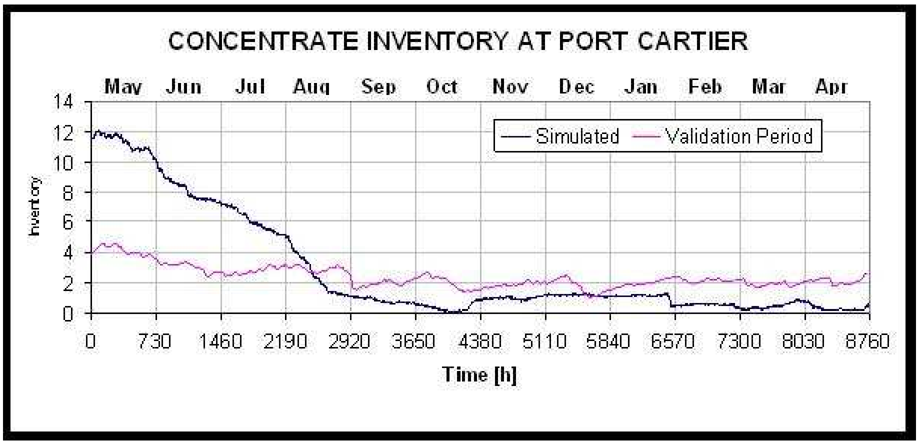

Figure 2: Concentrate inventory profile at port stockyard.

After alleviating the railroad constraints, explained in Section 3.3, the bottleneck shifted to port operations. Figure 3 shows the number of vessels anchored waiting to enter the inner harbour. An unacceptable number of vessels were queued during the peak summer traffic months resulting in heavy demurrage penalties under this scenario.

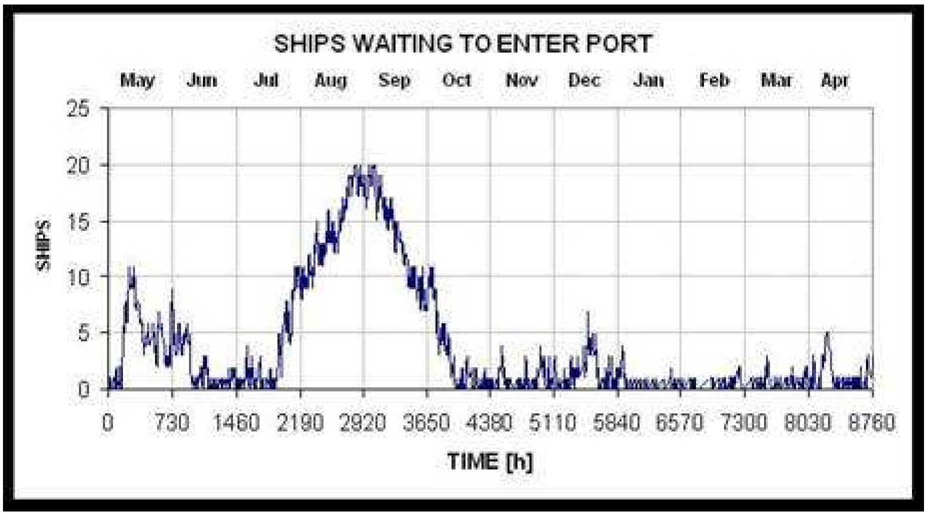

Figure 3: Number of ships waiting to enter port.

Alleviating the port constraints, explained in Section 3.4, in conjunction with rail debottlenecking initiatives, yielded a solution that satisfied the objective function. This general debottlenecking process was repeated, as new insights were revealed, to find a more optimal solution. Each expansion phase was analyzed in a similar manner.

3.3 Railroad Debottlenecking

Railroad debottlenecking dealt primarily with finding the optimal rolling stock inventory in terms of railcars per train, locomotives per train, number of consists in service and railcar axle loads as well as identifying the operational and track layout changes required to support increased production volumes. Figure 4 shows how much in-service railcar capacity is required (in combination with various investments and operational changes) as a function of iron ore export volumes.

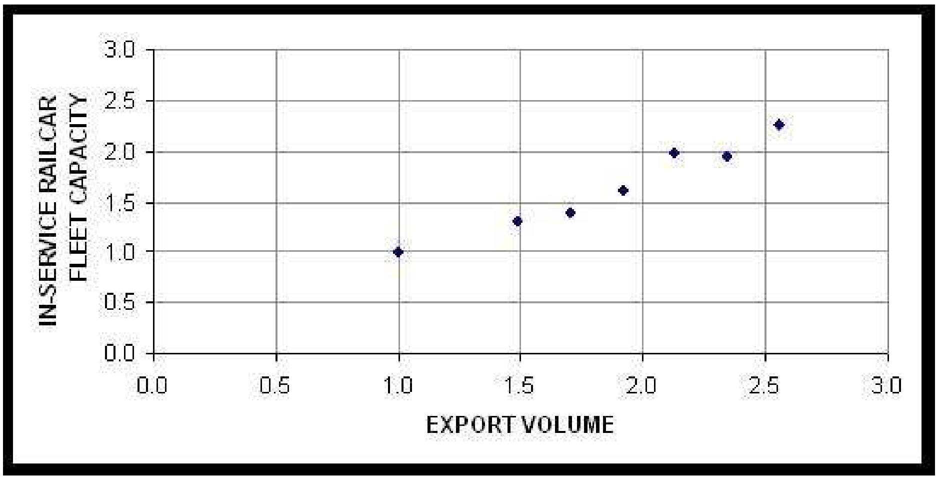

Figure 4: Railcar fleet capacity requirements.

Operational changes involved reductions in crew change times, reduction in the minimum time allowed between consecutive dispatches out of Port Cartier, and summer maintenance scheduling. Capital investments involved main line siding extensions, increased silo capacities at concentrators, dedicated yard locomotives, and additional track for queuing at the port and concentrator sites.

3.4 Port Debottlenecking

Port debottlenecking involved changing ship berth assignments, increasing shiploader capacity, and alleviating constraints related to simultaneous loading of ships and unloading of railcars in the port stockyard. Allowing a multiple shiploader scenario that involved simultaneous loading of ships with different ore grades had major implications on the material handling conveyor system. To simplify operations, re-assignment of berths for particular ore grades with an independent conveyor system and shiploader was a scenario that was considered. Regarding stockyard operations, the model showed that a stockpile capacity of about three times the current level would be required. This is primarily due to the reduced number of ships that came to port during the winter months. Also in the stockyard, rail dumper capacity needed to be increased to reduce excessive queuing of trains. Although not explicitly modeled, two new tug boats with higher horsepower were recommended due to the trend towards larger-capacity ships. A key objective of the port debottlenecking was to find a solution that did not increase ship times at port. Figure 5 shows a histogram of ship times at port for a simulated scenario and the validation period.

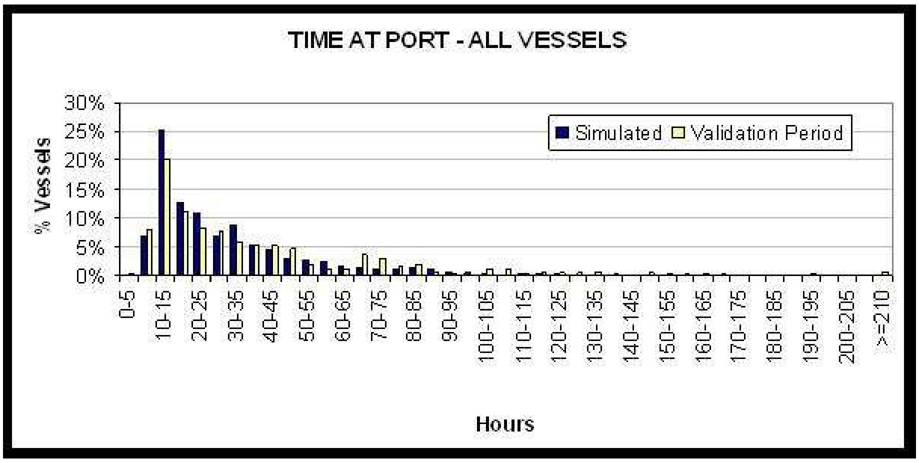

Figure 5: Ship times at port.

4 CONCLUSIONS

Simulation provided a powerful tool to better understand the system dynamics of the integrated "pit to port" operation, identify constraints limiting capacity, and test various what-if scenarios in search of an optimal solution to support phased capacity increases. Based on simulation results, a capital expansion program was formulated that defined the timing of capital investments and operational changes necessary to achieve expansion targets. By considering all phases of the expansion in a single study, the capital investment program was optimized in its totality, providing the option to bypass short term investments that have little or no benefit in later expansion phases by shifting the timeline of other capital investments.