SIMULATION OF LIQUID METAL LOGISTICS IN PRIMARY ALUMINUM INDUSTRY

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ABSTRACT

Production planning in the primary aluminum industry is a critical task, due to heavy imbalances among the main processes. As liquid production (reduction) has a very continuous and stable output, solidification at different lines have different operational paths (batch/continuous), shutdowns and variations in rates. Due to material's nature (hot liquid metal), it is not possible to maintain a buffer to absorb those imbalances. An adequate logistics planning for distributing liquid metal has to accomplish the solidification plan with an adequate usage of resources. In this paper we present the application of a simulation model to identify the main bottlenecks in the process, analyze dynamic system behavior, apply heuristics balancing algorithms and validate possible solutions for increasing casting capacity. The simulation model was implemented at Aluar's plant.

1   INTRODUCTION

Aluar is an Argentinian company producer of primary aluminum, located in Puerto Madryn, south of Argentina (see Figure 1). Its annual production capacity exceeds the 470,000 tons.

Logsis SRL is an Argentinian consulting company, focused in the application of simulation and other advanced computing tools. It has been part of the Paragontech Group since 2003.

The main goal of this study was to validate solutions for increasing rod solidification, considering different solutions to logistic bottlenecks.

As there is extensive literature about numerical simulation of aluminum melting process, there are no significant references about simulation of aluminum logistics.
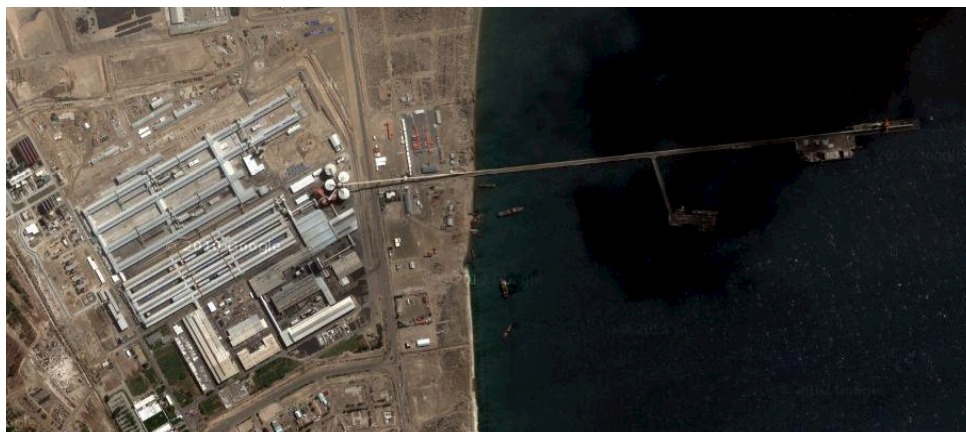

Figure 1: Satellite image of Aluar's Plant in Puerto Madryn, Argentina

1.1 Process Description

Aluar's reduction process consists of 784 pots distributed in eight potrooms. The reduction process is continuous; nevertheless the electrochemical pot cast operation to obtain the liquid metal is batch. After each batch is completed, liquid is transported to one of fourteen production lines, where it will be solidified in different products: standard Ingot, small Ingot, tee Ingot, prismatic ingot, zincalum sow Ingot, billet and rods. The whole process is represented in Figure 2.
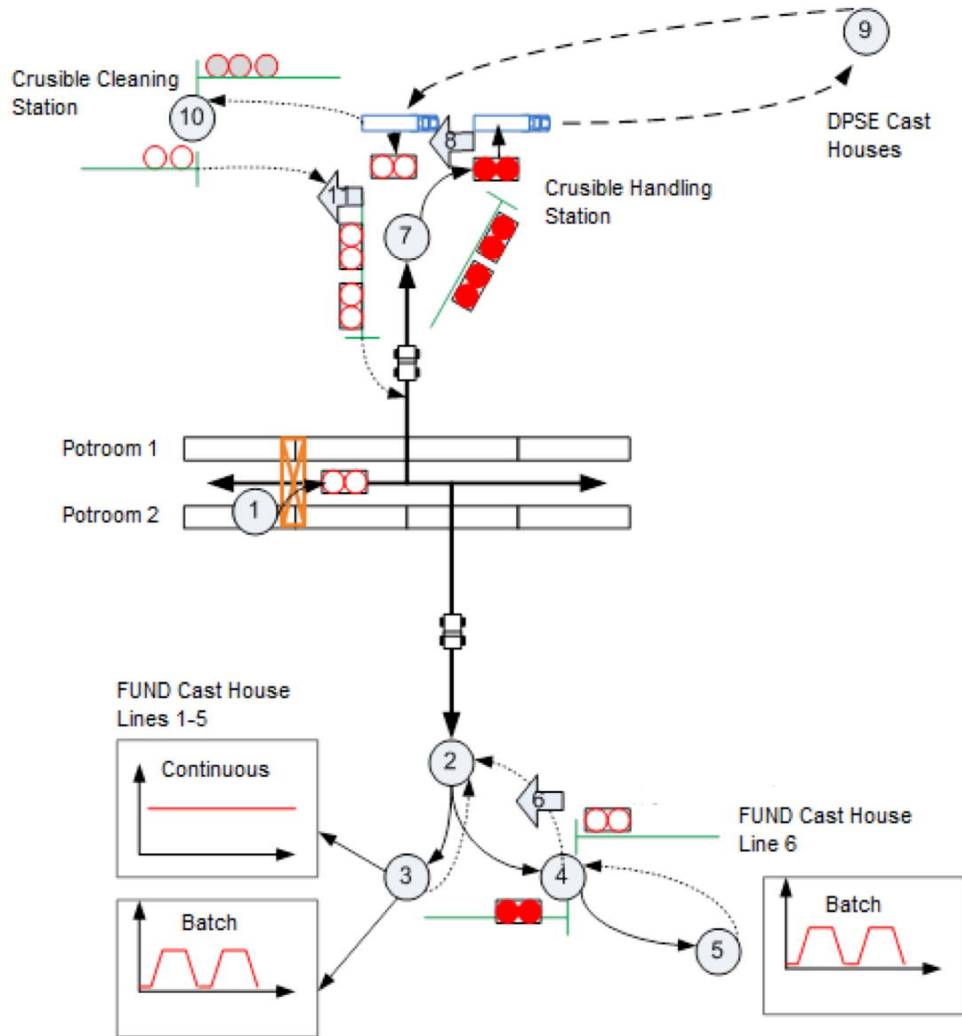

Figure 2: General process description

Reduction potrooms (1) are grouped in four electrical series (A, B, C and D). When the pot is tapped, the liquid aluminum is loaded in ladles (4-6 tons), loaded by pairs in carriages. Tractors will transport carriages towards two different cast houses: FUND (2-6) or DPSE (7-11). Carriages destinations are defined according to liquid stock and solidification needs (see subsection 2.2).

If the metal destination is a line on FUND, the tractor will transport the metal through a skimming operation (2), and then proceed towards the specified line:

- Lines 1 to 5 (3), where the liquid is dropped to a Buffer Furnace, which holds it until one of the Cast Furnaces is ready to receive it.

- Line 6 (4-5), which does not have a Buffer Furnace, so the liquid must be drop directly in the Cast Furnaces. These are located in a different level, below the main road where the tractors travel; at a transfer point a lift will descend the carriages to the lower level, where a dedicated transporter takes them and drops them in the furnaces.

As it can be seen Figure 2, there exists two kinds of solidification lines: continuous and batch production lines. Batch lines require to setup after casting the liquid of a single furnace, while continuous lines may cast a long period of time before requiring a setup.

When delivering metal to DPSE cast houses, it is necessary to transfer ladles from carriages to trucks (8) at the Crucible Handling Shop (CHS). At that site, a skimming operation is performed. After the metal is dropped at the specified line (9), the ladles are transported back to CHS (7). As shown in the picture, two queues are formed: queues of filled ladles waiting to be transferred to trucks, and queues of empty ladles waiting for tractors to get them back to Reduction.

Finally, the Crucible (ladles) Cleaning Station (10) is located inside the CHS. After every cycle, ladles' capacity is reduced by accumulation of slag, requiring periodical cleanings. This operation generates two new queues: dirty ladles waiting to be cleaned and already cleaned ladles waiting to be transported back to Reduction.

1.2 Problem Presentation and Objectives of the Study

Aluar is currently working on a project that would let them maximize rod production. Rods (Figure 3) are produced in two solidification lines, both located at the FUND cast house: lines 4 and 6. Line 4 is a batch production line, and has a Buffer Furnace and two Cast Furnaces. Line 6, though, is the critical line here, since it is a batch production line with two Cast Furnaces but no Buffer Furnace, and its dropping operation is more complicated than others, like it was shown previously. Increasing production in these lines requires major changes in specific processes, and has a significant impact in the logistics of liquid metal transportation, which has to be well studied to be able to satisfy a new production mix significantly more demanding.

Figure 3: Piles of rods ready to be shipped

The central question that originated this paper was, then, if it would be possible to supply both lines, taking into account logistic restrictions, so they could reach the desired production, without creating disturbances in the metal supply of the rest of the lines.

2 THE SIMULATION MODEL

Building a model from a complex system always requires an important job of abstraction through which define the greater and lower levels of detail that different parts of the model will require (Kelton, Sadowski and Sturrock 2007). Parts that will be defined without greater detail are usually called "black boxes". In this case, the premises adopted were the following:

- Aluminum obtained by Reduction is considered homogeneous, which is to say, quality will not be taken into account in the model's logic.
- Processes that occur after casting in solidification lines will be considered as black boxes.
- Internal transportation and processes in DPSE cast houses will also be considered as black boxes.

With this assumptions, the focus of the model was the internal transportation logistics of the process, which consists of liquid transported in ladles (carried by tractors) and the consumption of this liquid in each solidification line.

The model –developed by LOGSIS team using Rockwell's Arena® (version 13.5)– was structured in four main conceptual modules (see Figure 4): *Reduction*, *Prioritization Logic* (for the selection of the destination of the liquid metal), *Transportation*, and *Programming and Liquid Metal Consumption in Lines*. An interface was also created for the model, where input and output data was presented.
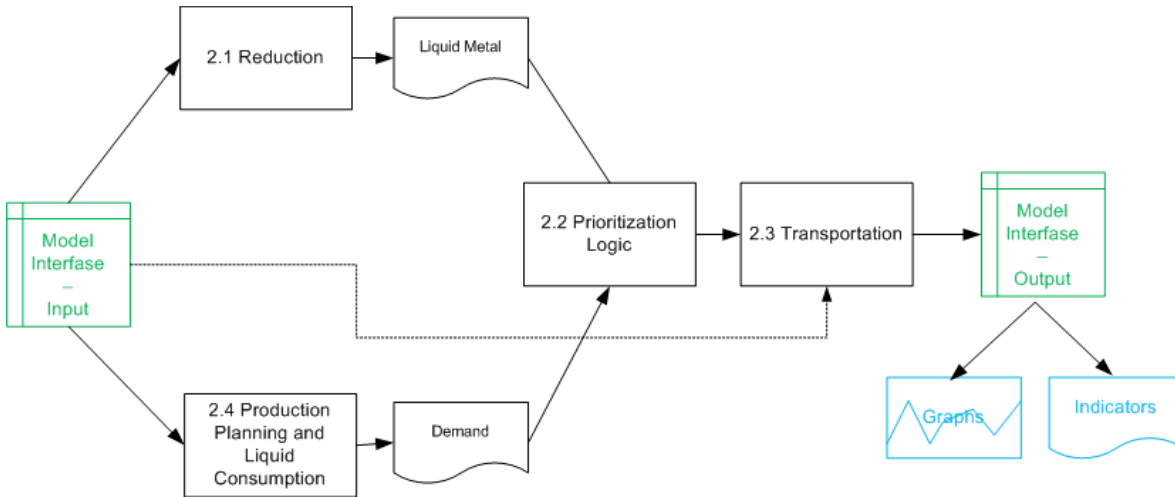
Figure 4: Conceptual modules of the simulation model

2.1   Reduction

Reduction sequences were modeled by control loops. The working sequences determine which reduction group is working every half-turn (4 hours). Each reduction group has its entering queues, were entities (ladles grouped in pairs) wait until they can be filled with liquid metal. Once filled, they wait in output queues until a tractor (modeled by Arena transporters) arrives. Since every reduction group must try to work continuously, a variable is defined to signal the need of a new set of ladles before the current set is full; this variable is set in the interface.

2.2   Prioritization Logic

This module is central to the model, since it determines the solidification line to which the liquid metal will be sent after reduction. This module will select the best candidate for the aluminum to be sent. To do so, the following variables were defined:

- Liquid in Line: This parameter represents the liquid present in the solidification line's furnaces (Cast and Buffer Furnaces), as well as the liquid "in transit", which is the liquid already being transported to the line.
- Security Level: This parameter is set in the interface for every solidification line in the cast houses. It represents the minimum level of "Liquid in Line" that each line is expected to have.
- Maximum number of trains reserved: This parameter limits the amount of trains that may be sent to each line simultaneously. It is also set in the interface.

The prioritization logic (see Figure 5) must compare the difference between the Liquid in Line and the Security Level for each line: the line with the highest difference will be proposed as the best candidate, but only if the amount of trains traveling towards that line is not greater than the Maximum number of trains reserved.
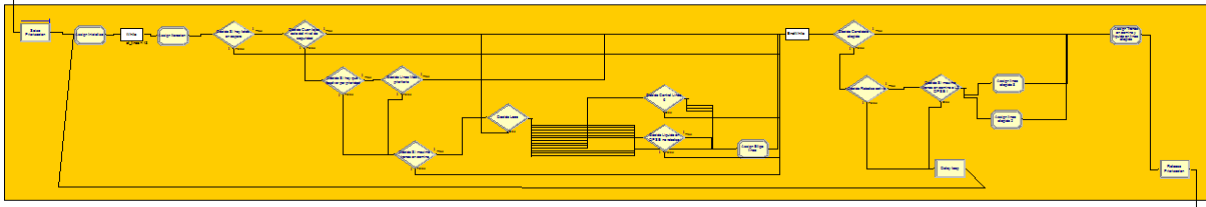

Figure 5: Overview of the prioritization logic in Arena®

In the real system, there exist "implicit common sense" rules between different sectors that administrate the relation between supply and demand of liquid metal. Through the validation process (described in section 3), it was shown that the above algorithm simulated the implicit rules with good precision.

2.3   Transportation

This block simulates the transportation process once a destination line is selected. Travel times are calculated internally by Arena, taking into account the tractor's (transporters) velocity means and roads' measures (roads are modeled by Network Links in Arena).

As it was described previously, lines 4 and 6 are both critical to this analysis. While the dropping operation for the first one is simple, the operation in the second one must be modeled in full detail. The lift, which transports ladles from the upper to the lower level –and back–, is modeled by an Arena resource; since this was described as a potential bottleneck of the whole process, its parameters are accurately set and its occupation is properly monitored. A transporter simulates the behavior of the dedicated transporter that takes the ladles out of the lift (one at a time) to drop them in the Cast Furnaces. Finally, two critical queues are defined: one queue for the full ladles waiting to be transported down by the lift, and a queue for empty ladles that had been transported back to the upper level and must wait for a tractor.

Transportation to DPSE cast houses is modeled in less detail. Operations in the Crucible Handling Shop (CHS), like skimming or transference of ladles to trucks, are properly simulated, but the operations that occur after trucks have left CHS are defined as a "black box".

Finally, dropping operation in each line is rather simply modeled, with the proper resources and loops that simulate the rate of the operation. Since animation (Figure 6) is central for the presentation, dropping loops allow a nice visualization of the furnaces filling.
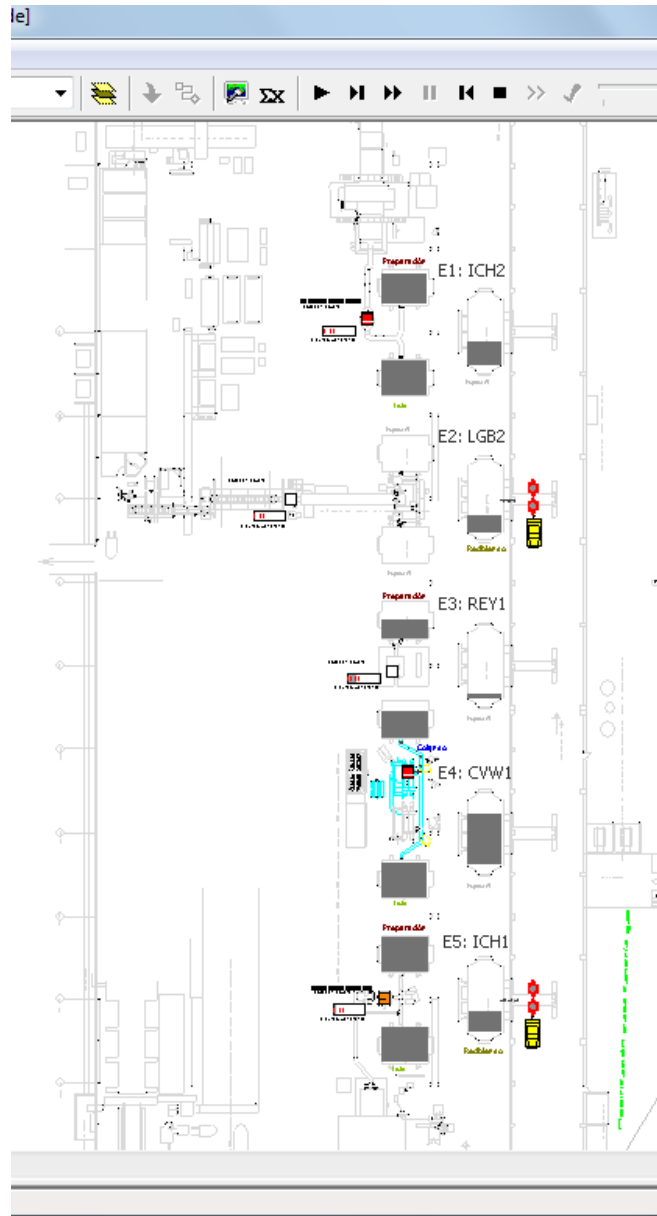
Figure 6: Model Animation - FUND Cast house

2.4   Production Planning and Liquid Consumption

Since the model is centered on the whole process of the liquid transportation and consumption, the production planning has to be properly described in the model to represent liquid demand from casting lines. Three submodels were defined: *Liquid Dropping from Carriages*, *Production Orders and Casting* and *Failures in Solidification lines*.

2.4.1 Liquid Dropping from Carriages

Buffer and Cast Furnaces are modeled as variables representing the level of each furnace. The capacity of each of these furnaces is set in the model interface. During the dropping process, the level of the corresponding furnace is incremented at a particular rate, which is also set in the interface. If the line has a Buffer Furnace, it is filled until its level reaches the capacity of a Cast Furnace; when this occurs, and the

dropping operation has finished, the transference operation starts. This operation consists on transferring the liquid from the Buffer to the Cast Furnace, and it is modeled by a loop that updates the furnaces' level variables at a proper rate. For this to be done, the selected Cast Furnace has to be empty and ready to be filled. (If the line does not have a Buffer Furnaces, the liquid is directly dropped to the Cast Furnaces.) Once a Cast Furnace is full, Preparation of the liquid in the furnace is simulated with a simple delay.

2.4.2 Production Orders and Casting

In the real system, the casting process follows real demand from clients. For this model, time between arrivals of production orders was modeled following real production data taken from Aluar database, which is entered to the model through its interface (so it could be changed whenever necessary).

An Excel sheet presents the parameters for each solidification line, as casting rates, batch sizes, and setup times, among others; from these parameters the model generates production orders randomly. Solidification lines are modeled as an Arena resource. Each production order requires the casting of the liquid in a Cast Furnace, and is queued to seize the line resource every time a Cast Furnace is ready to operate.

2.4.3 Failures in Solidification Lines

Analyzing historical behavior of the solidification lines, a failure profile was generated to each of them. This profile can be set in the model interface in a "Time between failures/Time of failure" fashion.

2.5 Observation

The thoroughness in the specification of Prioritization Logic (Section 2.2) and Production Orders arrivals (Section 2.4) is one of the most, if not the most, important aspects of the model. Full synchronization of aluminum transportation depends irrevocably from those submodels: Prioritization aims to properly supply liquid to each line, while Production Orders simulate its consumption. Any imbalance between these two submodels would cause the whole model to provide inaccurate results.

3 DATA ANALYSIS

Historical data analysis is an essential part of the modeling process. The only way we can validate if our specification is correct, is by constructing scenarios based on historical data, simulating them and then expecting its output to be as accurate as possible.

A comprehensive analysis of historical data was performed for several modules of the model: Production at solidification lines, Shutdowns at solidification lines, Production at Reduction, Distribution of quality in liquid aluminum, among others.

For each module described in section 2, a set of input parameters were defined in the model interface. By setting these parameters we define a scenario to be simulated by the Arena model. Also, a set of output parameters (indicators) and graphs were created on the interfase itself, so as to see the main results of the simulation and study the performance of the model.

4 MODEL VERIFICATION AND VALIDATION

After its construction was completed, the model was presented to Aluar's line management and senior operators in order to verify its realistic behavior and correct any misunderstandings in operational logic, premises and parameters.

A comprehensive animation of all relevant processes was presented, as well as comparative indicators among simulation output and historical data, regarding shutdowns, cycle times, transportation times, resources utilizations, solidification lines utilizations, among several others.

Before using the model to study future scenarios, it was necessary to validate its behavior with the real system (Kelton, Sadowski and Sturrock 2007). Through a thorough analysis of historical data, statisti-

cal distributions were defined for the parameters in the model interface in order to simulate a real scenario. The results obtained from the simulation were compared with historical indicators. After this procedure was repeated several times –adjusting the model after each iteration–, the model results showed that it represented the real scenario with a precision of ± 2%, considering liquid consumption at solidification lines as the main indicator.

5   ANALYSIS OF FUTURE SCENARIOS

Once verification and validation were completed, the model was ready to be used to study future scenarios. As it was stated on the introduction, rod production was to be maximized and its impact on the system behavior had to be studied. Three scenarios were defined (see Table 1), analyzing three possible situations for the future:

- First, we analyzed the results of improving production capacity in solidification lines 4 and 6, without introducing further changes in the system.
- Second, we introduced two buffer furnaces for receiving liquid metal in line 6, changing the logistics of the dropping operation for this line.
- Finally, the last scenario showed how the system would perform if, in addition to adding the buffer furnaces, the lift would be canceled (since it proved to be a bottleneck of the dropping operation in Line 6).

Table 1: Design of Experiments

	Production Capacity in Lines 4 and 6	Buffer Furnaces in Line 6	Lift in Line 6
Scenario 0	Actual	No	Actual
Scenario 1	Improved	No	Actual
Scenario 2	Improved	Yes	Actual
Scenario 3	Improved	Yes	No Lift

The main variables analyzed for each scenario were line productions and utilizations, particularly for lines in the FUND Cast house. Another critical indicator was the "delayed pots" one. Every work turn, a predetermined amount of liquid metal is generated in the potroom; the metal that could not be loaded into ladles and remained in the pots at the end of the turn is accounted to the "delayed pots" indicator. Trains' queues in FUND Cast houses are thoroughly analyzed, as well as the resources used for dropping operations in each line. Finally, equipment utilization, such us tractors, is of great relevance too.

For each scenario to be simulated, the necessary changes had to be introduced in the model interfase. In order to increase production in one line, other lines' production had to be decreased. This analysis of the new input data was performed with Aluar's operators, who had performed previous studies to determine what would make a sensible production mix for future scenarios.

5.1   Analysis of Results

Each scenario is progressively more demanding to the logistics of liquid metal supply, stressing the coordination required and demanding fine tuning to the controlling heuristics. We found that a four-months running, with a one-month warm-up period, was enough to obtain steady state results of this system, as shown in Figure 7. Several replications of each scenario were performed and it was verified that statistical variations were not significant.
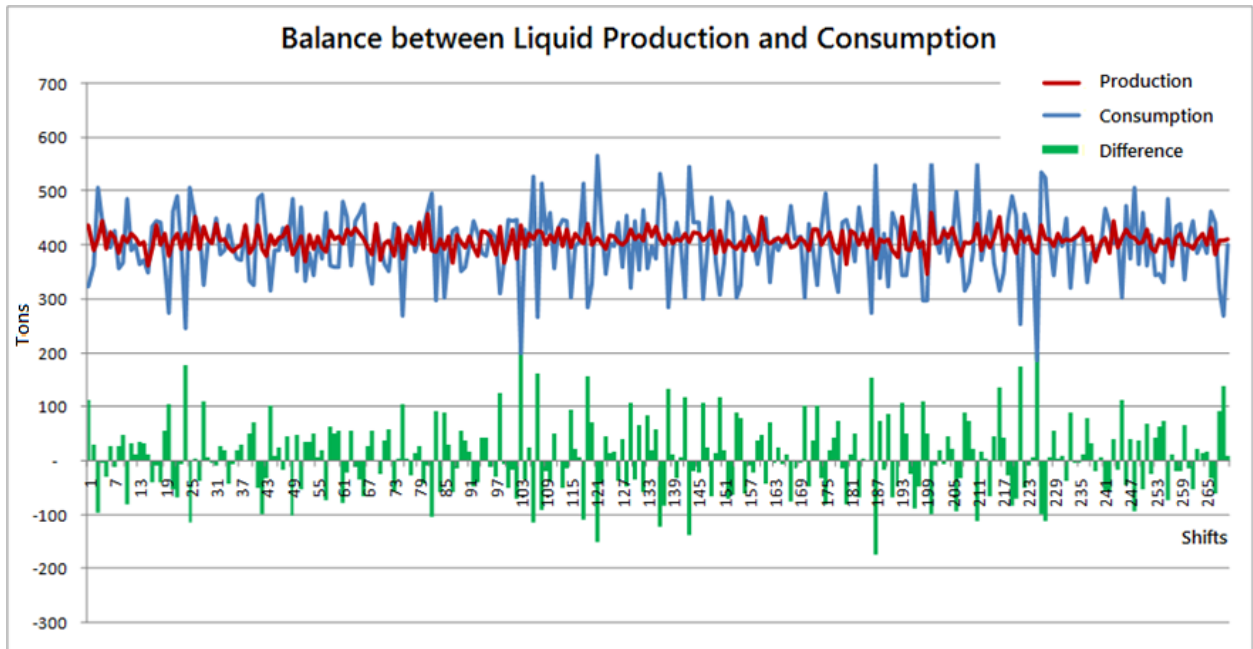
Figure 7: Steady State Results

5.1.1 Scenario 0

Scenario 0 refers to the validation scenario, and it is included just to compare and analyze the progressive impact of each proposal.

5.1.2 Scenario 1

Scenario 1 does not imply model modification, just changing parameters in the configuration of Lines 4 and 6, specially their setup and casting furnace's preparation times. These changes where discussed and proposed by Aluar. The verification of their impact on the system's performance was required, before continuing with further scenarios.

Results rapidly showed that Line 4, continuous line with a buffer furnace, could increase its production by approximately a 45% just by optimizing its internal operations. Performance of Line 6, batch line with no buffer furnaces, was not affected by these changes, which confirmed that its internal operations were not critical at this stage. The overall rod production was increased by a 34% and the rest of the solidification lines were behaving correctly. Performance indicators on several resources also showed good results.

5.1.3 Scenario 2

Simulation of Scenario 2 required structural changes in Line 6: adding two buffer furnaces and changing its supply logistics. Without buffer furnaces, since dropping and casting operations in the Cast furnaces had to be sequenced (both operations could not happen simultaneously on the same furnace), liquid metal supply was not optimal.

A new logic had to be created in the model for the new dropping operation. Carriages arriving to this line would descend (using the lift) and the dedicated transporter would drop the liquid into the new buffer furnaces. This procedure would allow line 6 to be able to receive liquid efficiently.

The impact of this change proved to be of great significance, increasing rod production by approximately a 40% in Line 6, while maintaining scenario 1's improvement in Line 4. Tractors and ladles' utili-

zation was significantly increased, but it was far from being unreasonable. The overall rod production, compared to Scenario 0, had been increased by a 71%.

Analyzing the queue of trains waiting to descend, average waiting time showed a bottleneck at the lift of Line 6.

5.1.4 Scenario 3

Scenario 3 simulated a situation where carriages would not have to use the lift, since trains would be able to reach the furnaces' level following a different path. The results showed that without this restriction, the transportation system could reach the rod production goal, while reducing waiting time in Line 6's queue and tractor utilization. The overall rod production had been increased by an 85%.

6   CONCLUSIONS

Figure 8 shows the comparative analysis of the results of each model, focusing on rod production. Scenario 3 reaches goal production with a precision of ±1%, which shows that the supply of liquid metal is feasible.
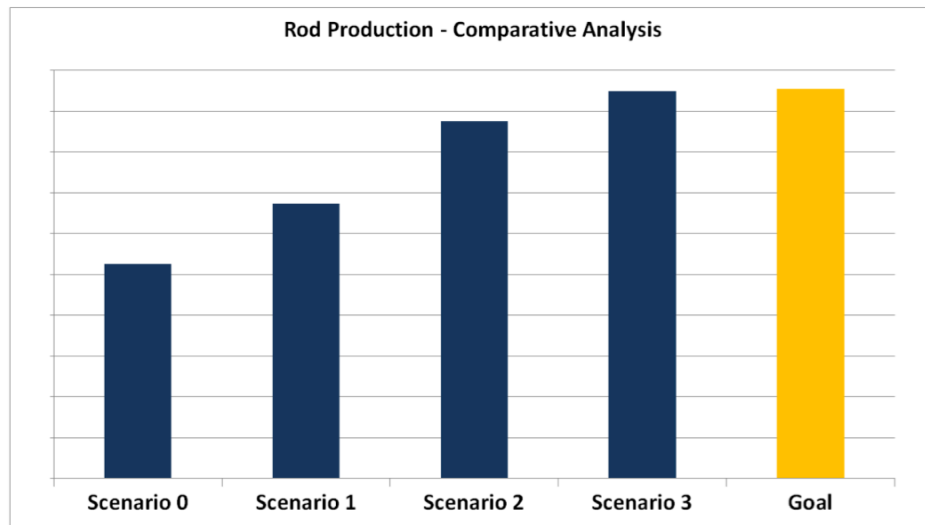

Figure 8: Comparative Analysis (chart is not in real scale).

The simulation model demonstrated the feasibility of increasing rod production while being able to supply the rest of the solidification lines, as it can be seen in Scenario 3 results. With no improvements in lift system it would be impossible to reach the desired production level.

Scenarios 1 and 2 can anticipate the impact of partial stages of Aluar plant's modifications, before reaching the final stage presented in Scenario 3.

From that last scenario, it was also concluded that a proper coordination in the system's logistics is required, since the model needed a very thorough set up of its parameters to reach the production goal. It is especially remarkable that a relatively simple heuristic could reach a good planning performance, replacing a very complicated coordination process used in day by day operation.

Other important conclusion was that new Buffer Furnaces would reduce consumption peaks and reduce queues at the street entering solidification lines, though traffic would be manageable.

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