UNIVERSIDADE FEDERAL DE MINAS GERAIS
Escola de Engenharia
Programa de Pós-graduação em Engenharia de Recursos Minerais

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Dynamic Simulation of a Port Terminal Shipment Operation for Iron Ore Exportation

Belo Horizonte
2023

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Dynamic Simulation of a Port Terminal Shipment Operation for Iron Ore Exportation

Monografia de especialização apresentada à Escola de Engenharia da Universidade Federal de Minas Gerais, como requisito parcial à obtenção do título de Especialista em Engenharia de Recursos Minerais.

Orientador: Luiz Cláudio Monteiro Montenegro

Belo Horizonte
2023

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Realizou-se, no dia 27 de fevereiro de 2023, às 09:00 horas, na plataforma MEET, da Universidade Federal de Minas Gerais, a defesa do Artigo, intitulado "DYNAMIC SIMULATION OF A PORT TERMINAL SHIPMENT OPERATION FOR IRON ORE EXPORTATION", apresentado por EDENILSON JOSÉ DA SILVA FILHO, número de registro 2021697457, graduado em ENGENHARIA QUÍMICA, como requisito parcial para a obtenção do certificado de Especialista em ENGENHARIA DE RECURSOS MINERAIS, à seguinte Comissão Examinadora: Professor Luiz Claudio Monteiro Montenegro - Orientador, Professor Roberto Galery (Universidade Federal de Minas Gerais), Professor Michel Melo Oliveira (Universidade Federal de Minas Gerais).

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Resumo

Este estudo avalia uma operação de embarque portuário para exportação de minério de ferro para Europa e Ásia. Retomadoras de caçamba, com capacidade nominal de 8 ktph cada, recuperam o material das pilhas. As capacidades dos transportadores a jusante e o padrão de recuperação irregular, acentuado por variações de fim de cone e fim de pilha, impedem a operação de pico simultânea das retomadoras, o que resulta em taxas de carregamento de navios abaixo da capacidade nominal. Um modelo de simulação dinâmica foi construído no Arena®, combinando as capacidades de embarque e de retomada, número de retomadoras e possível inclusão de um silo de regularização. Os resultados indicaram a necessidade de um novo silo de regularização, além de definir sua capacidade (1 000 t).

Palavras-chave: Minério de Ferro. Simulação Dinâmica. Regularização de Taxa de Embarque.

Abstract

This study evaluates a port shipment operation to export iron ore to Europe and Asia. Bucket reclaimers, with 8 ktph nominal capacity each, recover material from stockpiles. Downstream conveyors capacities, and irregular reclaiming pattern, accentuated by end-of-cone and end-of-pile variations, prevent reclaimers simultaneous peak operation, which results in ship loading rates below nominal capacity. A dynamic simulation model was built in Arena®, combining shipping and reclaiming capacities, number of reclaimers and possible inclusion of a regularization bin. Results indicated the need for a new regularization bin, besides defining its capacity (1 000 t).

Keywords: Iron Ore. Dynamic Simulation. Shipment Regularization.

Illustrations List

Figure 1. Iron ore imports by country in 2021[3] 8
Figure 2. Port shipment operation block flow diagram 9
Figure 3. Reclaiming profile of an 8 ktph nominal capacity bucket reclaimer 10
Figure 4. Data analysis chart[5] 11
Figure 5. Individual reclaimer flowrates histogram 14
Figure 6. (a) TBF and (b) TTR duration histograms....15
Figure 7. Ship's total feed rate in (a) real operation and (b) base case simulation 16
Figure 8. New (a) 8 ktpa and (b) 16 ktpa reclaimers operation in option 2 18
Figure 9. Shipment rate regularization block flow diagram 19
Figure 10. Regularization simulation with two simultaneous reclaimers: (a) Ship loading rate, (b) Bin inventory variation 20
Figure 11. Regularization simulation with three simultaneous reclaimers: (a) Ship loading rate, (b) Bin inventory variation 21

Tables List

Table 1. Reclaimers statistical distributions....14
Table 2. TBF and TTR statistical distributions....15
Table 3. Shipping capacity increases for higher reclaiming capacity options....18
Table 4. Shipping capacity increases for higher ship loading capacity options....19
Table 5. Shipping capacity increase for shipment rate regulatization....21
Table 6. Shipping capacity increases for all simulated design improvements....22

Summary

1. Introduction 8
   1.1 Iron Ore Exportation Logistics 8
   1.2 Studied Iron Ore Port Terminal 9
2. Theoretical Background 11
   2.1 Dynamic Simulation 11
3. Methodology 12
4. Results and Discussion 13
   4.1 Data statistical analysis for modelling 13
      4.1.1 Reclaimers data 13
      4.1.2 Failures data 15
   4.2 Base case simulation 16
   4.3 Design improvements simulation 17
      4.3.1 Higher reclaiming capacity 17
      4.3.2 Higher ship loading capacity 18
      4.3.3 Shipment rate regularization 19
   4.4 Design improvement selection and implementation 21
5. Conclusions 22
6. References 23

1. INTRODUCTION

1.1 Iron Ore Exportation Logistics

One of the main commodities in the world, iron ore is primarily used for steel production, which accounts for 98% of its global consumption. In 2021, international production was estimated at 2,537 million tonnes, with price fluctuating from US$116 to US$214 per tonne, depending on each month's demand.[1] Iron ore is usually commercialized as lump (small blocks), sinter feed (fine product) or pellet feed (further screened material), the latter being the most common in the market.[2]

As the major global consumers, Asian countries are also the main iron ore importers, with 89% of the worldwide accounted expenditure in 2021. Europe comes in the second place, with 8.7% of the importation spending. A breakdown of the main importing countries is given in Figure 1.[3]

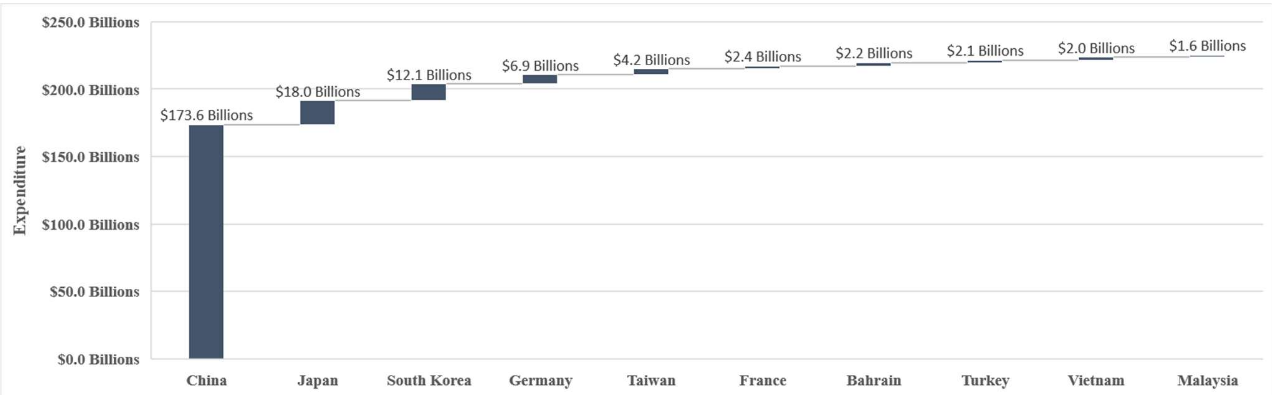


Figure 1. Iron ore imports by country in 2021[3]

The high transportation volumes add complexity to iron ore's supply chain, which is subject to challenges such as cost, security of supply and inventory management. Port terminal operations involve varied loading and unloading rates and quantities, always aiming to ship iron ore in the consignment size required by consumers. In this context, iron ore producers with integrated mine-rail-port logistics are often the most efficient. By owning and operating their own ports, railways and even ships, these companies can achieve increased capacity, improved inventory management and higher profitability.[4]

In order to meet their growing overseas clients demands, iron ore producers with integrated transportation logistics located outside Asia and Europe, the main consuming regions, must invest in strong and reliable shipping operations in their port terminals. Reclaimers, conveyors and ship loaders capacities and availabilities often restrict achieved shipping rates, with logistics gaps from the stockpile reclaiming to ship loading. Considering the growing external consumption, addressing these issues to optimize port operations can prove itself a valuable improvement, resulting in increased exportation capacity and higher sales profits.

1.2 Studied Iron Ore Port Terminal

Inserted in this global scenario, the studied port terminal located in South America is part of an integrated mine-rail-port operation to export iron ore to the main global consumers in Europe and Asia, transporting hundreds of millions of tonnes per year.

Five ships can be accommodated at the same time, and 95% of the material handled in this port terminal is sinter feed. The iron ore is received by car dumpers, and stored in longitudinal stockpiles distributed in two independent yards (A and B). bucket reclaimers are responsible for recovering this material, sending it to belt conveyor and shiploader systems that load the ships. A block flow diagram of the port is given in Figure 2.

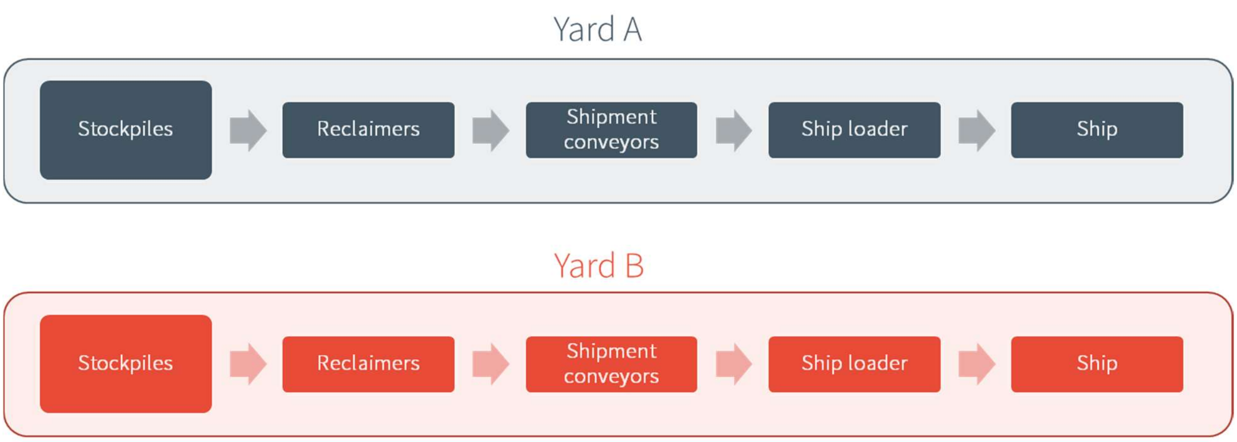


Figure 2. Port shipment operation block flow diagram

The bucket reclaimers have 8 ktph nominal capacities, but can reach higher peak rates. These rates are subject to large variations depending on the position of the reclaimer, with substantial decrease in pile ends and pile shifts. An example is given in Figure 3, showcasing an operation with average reclaiming rate of approximately 6.2 ktph.

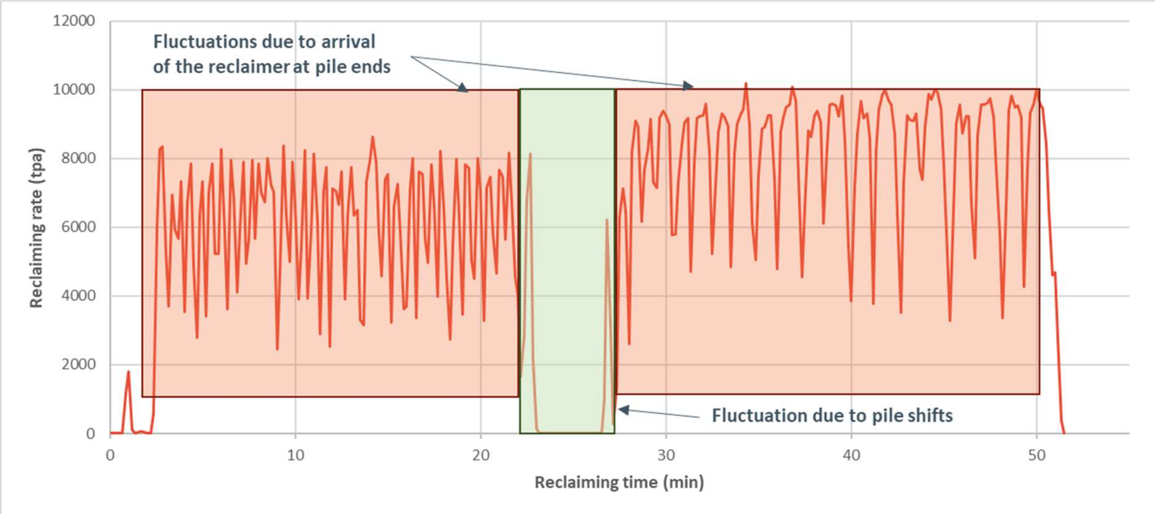


Figure 3. Reclaiming profile of an 8 ktph nominal capacity bucket reclaimer

The terminal configuration allows for multiple reclaimers feeding one line of shipment conveyors up to a total capacity of 16 ktph. However, given the reclaiming rate fluctuating behavior, conveyors total capacity of 16 ktph restrain the operation with multiple reclaimers at the same time: a maximum of two simultaneous reclaimers is allowed, since the inclusion of a third one could extrapolate the conveyors transporting capacity during peak reclaiming rates. Even when two reclaimers are operating simultaneously, the sum of peak rates on both machines can surpass conveyor capacity and lead to overload of the shipping line. This issue, combined with the reclaiming fluctuation, results in ship loading rates below nominal capacity, limiting the port's iron ore exportation capacity.

Aiming at optimizing operations in this port terminal and increasing loading capacity, this study developed a dynamic simulation model to assess the port shipment process, with bottlenecks and opportunities identification. Based on the assessment, new engineering solutions were proposed and modelled, to quantify the associated benefits in terms of exportation capacity increase.

2. THEORETICAL BACKGROUND

2.1 Dynamic Simulation

Working as a data analysis method, dynamic simulation can be used in cases where variables present high codependences, interrelations, and process variability, as illustrated in Figure 4. Operational complexity is an integral part of the model simulation, including equipment dynamics, failures frequency and duration profiles. Integrated analysis allows a better estimation of the system and identification of risks and opportunities, which can also be incorporated in the model for further simulation.[5]

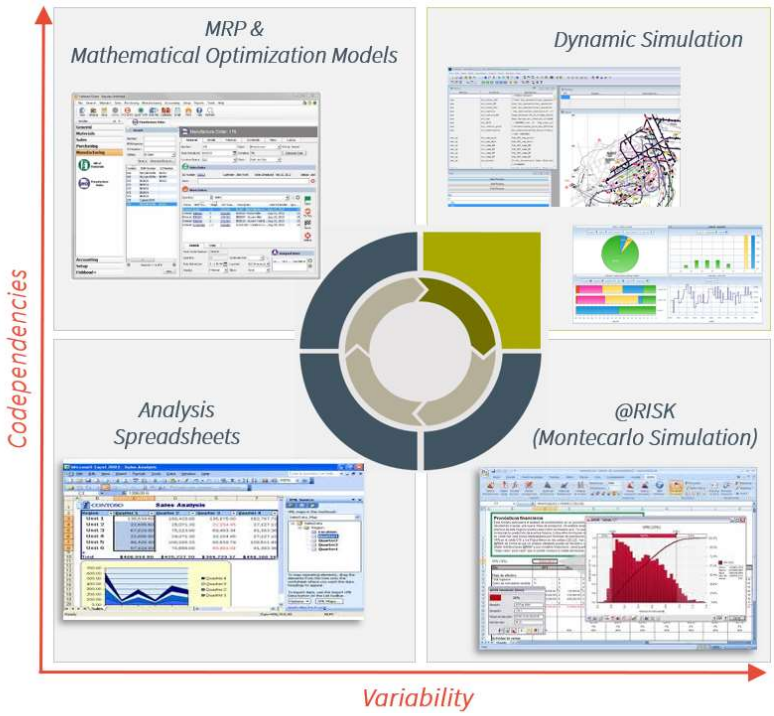


Figure 4. Data analysis chart[5]

In dynamic simulation models, equipment and operations are modelled by interconnected nodes, each of them containing representative statistic distributions of the main variables and how they can be affected by eventual failures. The level of accuracy of this type of study is very dependent on the information level of the input data. Therefore, it is essential to have a reliable and representative set of available data, supported by adequate statistic summarization.[5]

One of the main advantages of dynamic simulation is the establishment of a risk-free virtual environment that allows evaluating a wide range of scenarios and the behavior of the system under different operational conditions. This results in lower cost and higher flexibility to achieve business improvement.[5]

3. METHODOLOGY

The study was based on a set of material movement data, combined with ship loading history and also movement, unloading and loading rules available within the range of a year of operation. Since sinter feed corresponds to over 95% of the total iron ore handled in this port, the study was limited to the movement of this material, so that proposed solutions result on significant gains in capacity.

For the port optimization study, a dynamic simulation model was developed in Rockwell's Arena® software, aiming to identify bottlenecks and opportunities for improvement in port operation with the goal of increasing the shipping rate. The optimization model covers the entire port operation with hourly resolution, including from the material reception (car dumpers) to the ships loading. The main variables considered for the modelling were:

- Unplanned outages
- Ship capacity
- Reclaiming capacity
- Reclaimer curve
- Number of reclaimers (max. 3 due to conveyors capacity restriction)
- Bin capacity (for scenarios with regularization bin inclusion)

Engineering improvements that allow a better operation of the port were proposed, considering the distribution of sinter feed in the yards, boarding priorities, ships scheduling, among others, with the objective of increasing shipping capacity. The design options evaluated in the study were:

- Higher reclaiming capacity:
  - New reclaimers
  - Existing reclaimers power increase
- Higher ship loading capacity:
  - Ship loader power increase
- Shipment rate regularization:
  - Addition of a regularization bin

These scenarios were also modelled in Arena®. Each simulation was replicated 10 times to ensure an adequate statistical sensitivity of the model. The shipping capacity increase for each one was estimated, comparing to real data, in order to assess the benefits and define the most adequate engineering solution for the port operation.

4. RESULTS AND DISCUSSION

4.1 Data statistical analysis for modelling

In order to obtain distributions to represent the main parameters in the Arena® modelling, a statistical assessment of the available set of data was provided.

4.1.1 Reclaimers data

The individual profiles of all bucket reclaimers presented a similar behavior, but around different modal flowrates. As an example, the histogram for one of the reclaimers is shown in Figure 5.

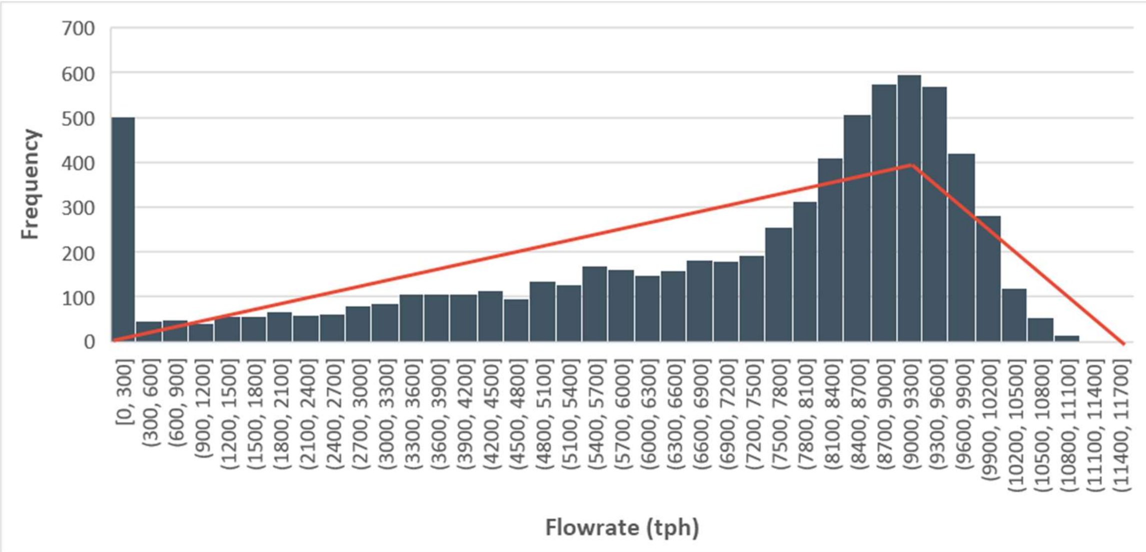


Figure 5. Individual reclaimer flowrates histogram

The histogram shows that the instantaneous recovery rates are concentrated in one point (recovery setpoint), but that they have a long variation, with a certain concentration in values close to or equal to zero.

The Input Analyzer software was used to determine the distribution that best fits the reclaimers' profiles, resulting in a triangular distribution. The triangular distribution (TRIA) presents a linear behavior between a minimum value and an average value, and another linear behavior between the average value and the maximum value. These parameters are presented, for the three statistical curves used for the modelling, in Table 1.

Table 1. Reclaimers statistical distributions

Scenario	Statistical Distribution (tph)
Worst reclaimer	TRIA(0;7,930;10,700)
Average reclaimer	TRIA(0;7,590;12,400)
Best reclaimer	TRIA(0;9,900;12,400)

4.1.2 Failures data

Based on this history of ship loadings, it was possible to determine the stoppages for corrective maintenance that occurred in the port during periods of shipment. These data are representative so that the dynamic simulation model reflects real problems during the shipping operation.

The time between failures (TBF) and time to repair (TTR) data for each operational problem that occurred during shipment operations were used to build two histograms, which are presented in Figure 6.

(a) (b)

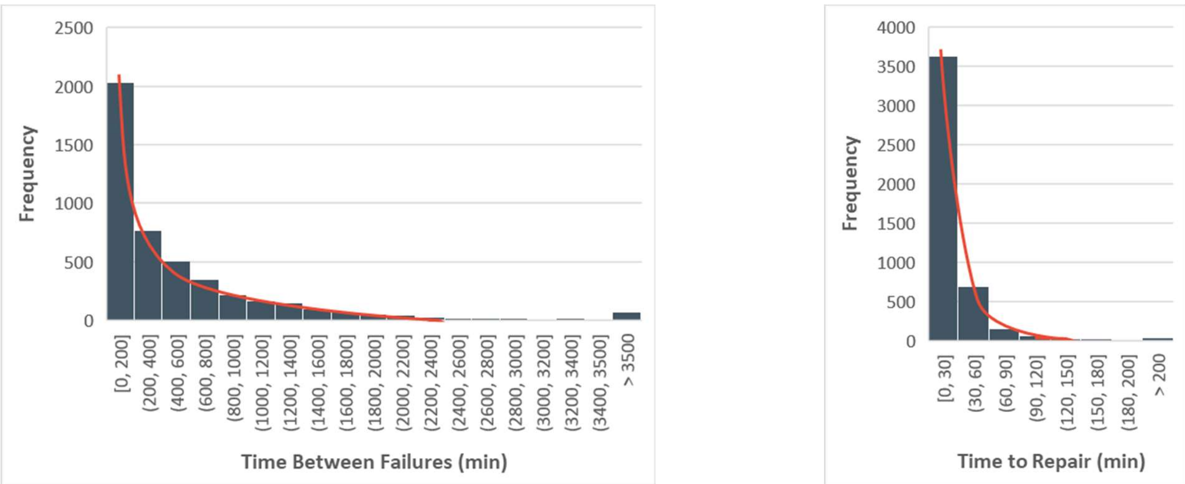


Figure 6. (a) TBF and (b) TTR duration histograms

From the histograms, statistical distributions that best represent the TBF (exponential function) and TTR (Weibull distribution) were obtained, using Input Analyzer, as shown in Table 2.

Table 2. TBF and TTR statistical distributions

Scenario	Statistical Distribution (min)
Time between failures (TBF)	EXPO(77.3)

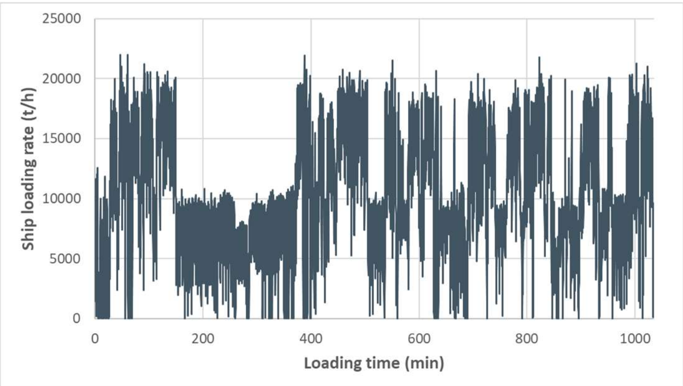
Scenario	Statistical Distribution (min)
Time to repair (TTR)	WEIB(20.3; 0.782)

4.2 Base case simulation

Used for model calibration, the base case for the simulation consisted of replicating the loading of a 180,000 tonnes capacity ship, for which real data were available for comparison. Failure times were not considered for this specific simulation since there were no outages in the original shipment. Therefore, only the actual time in which the reclaimers were working and directing material to the ship was represented.

The ship's total feed rate is given in Figure 7, for both reference operation and simulated base case. Two simultaneous reclaimers were always used for shipment, except for the 200 min to 400 min period in the reference operation, during which only one reclaimer was available.

(a) (b)



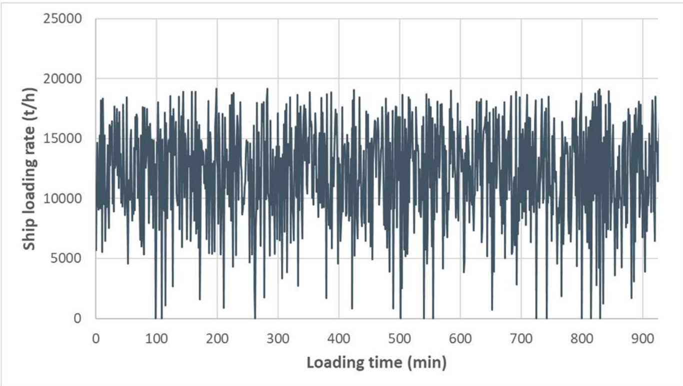


Figure 7. Ship’s total feed rate in (a) real operation and (b) base case simulation

The base case simulation resulted in a ship loading profile comparable to the reference shipment, with high instantaneous rate variability due to reclaimer load at end of pile and end of pile shifts. The simulation showcased the necessity of 15.4 h of operation with two simultaneous reclaimers to load the 180,000 tonnes capacity ship, and the real operation’s duration was 17.2 h. Considering the downtime period of one of the reclaimers in the reference operation (which increases total loading duration), the results are comparable and indicate an adequate calibration of the model.

4.3 Design improvements simulation

Three proposed design improvements were assessed, with the associated shipping capacity increases quantified through modelling, as described in the following subsections. The results were used to select the most adequate improvement for implementation in the port terminal.

4.3.1 Higher reclaiming capacity

Reclaiming capacity can be increased through repowering of the existing reclaimers, or acquisition of new reclaimers. Three main options were simulated in the dynamic model:

- Option 1: substitution of two existing 8 ktph bucket reclaimers by two new 16 ktph bucket reclaimers
- Option 2: acquisition of one new 8 ktph bucket reclaimer and one new 16 ktph bucket reclaimer
- Option 3: acquisition of one new 8 ktph bucket reclaimer and repowering of one existing 8 ktph bucket reclaimer to reach new capacity of 12 ktph

Modelling results showed the first option is the only one that actually increased overall shipping capacity. A higher number of reclaimers (as proposed in options 2 and 3) does not necessarily result in higher shipping capacity, because of the reclaiming dynamics and safety restrictions associated to the downstream conveyors capacity of 16 ktpa. As an example, the first new reclaimer inserted in option 2 would spend much time out of operation (blocked), because the other reclaimer already occupies most of the shipping capacity, as illustrated in Figure 8.

(a) (b)

Figure 8. New (a) 8 ktpa and (b) 16 ktpa reclaimers operation in option 2

The resulting improvements in terms of shipping capacity for the three options are quantified in Table 3.

Table 3. Shipping capacity increases for higher reclaiming capacity options

Option	**Description**	**Annual Shipping Capacity Increase**
1	Substitution of two existing 8 ktpa bucket reclaimers by two new 16 ktpa bucket reclaimers	3.1%
2	Acquisition of one new 8 ktpa bucket reclaimer and one new 16 ktpa bucket reclaimer	0
3	Acquisition of one new 8 ktpa bucket reclaimer and repowering of one existing 8 ktpa bucket reclaimer to reach new capacity of 12 ktpa	0

4.3.2 Higher ship loading capacity

An increase in the loading capacity can be achieved through repowering of the ship loaders. The analysis was conducted considering two alternative loaders that could be repowered from the current 8 ktph capacity to reach a new capacity of 16 ktph. The improvement quantification of both modelled options is given in Table 4.

Table 4. Shipping capacity increases for higher ship loading capacity options

Option	Description	Annual Shipping Capacity Increase
1	Pier A ship loader repowering to 16 ktph	1.5%
2	Pier B pier ship loader repowering to 16 ktph	2.3%

4.3.3 Shipment rate regularization

For this design improvement, it was considered the insertion of a regularization bin in yard B. In this concept, several reclaimers direct material to this bin, which then distributes the sinter feed to the ships, as illustrated in Figure 9.

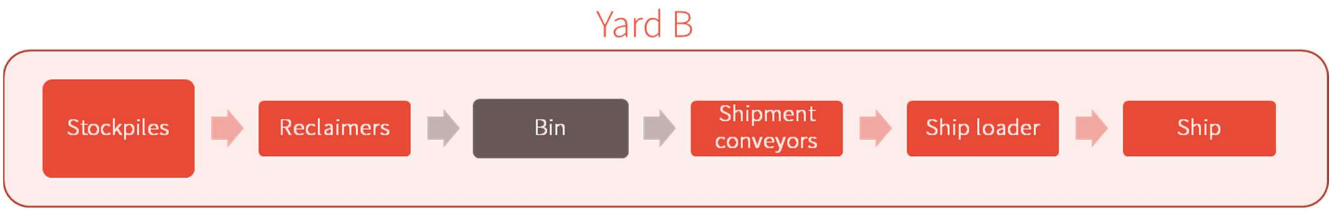


Figure 9. Shipment rate regularization block flow diagram

The simulation was initially carried out considering two simultaneous reclaimers functioning, such as in the current terminal operation philosophy. Resulting loading rates and bin inventory variation are shown in Figure 10.

(a) (b)

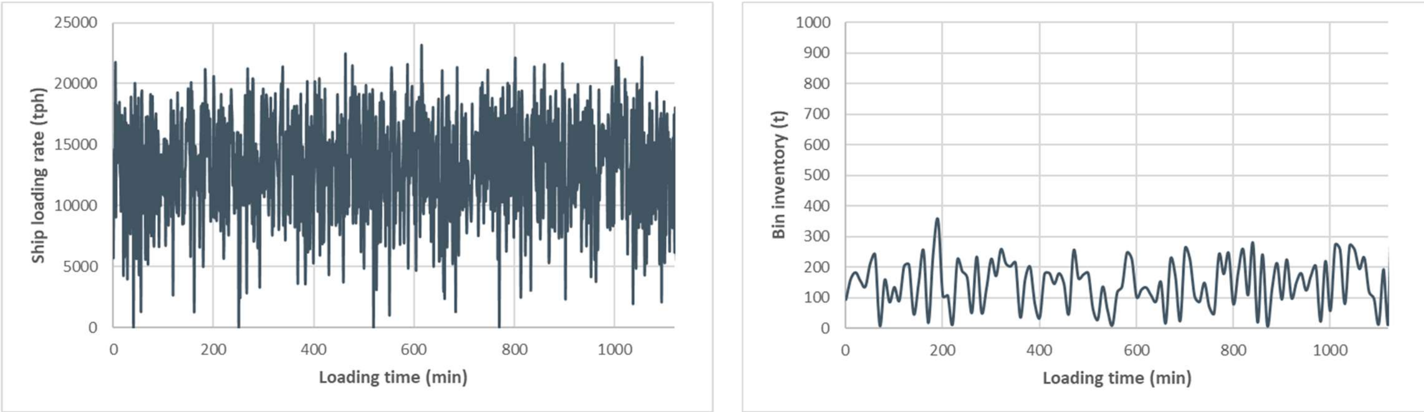


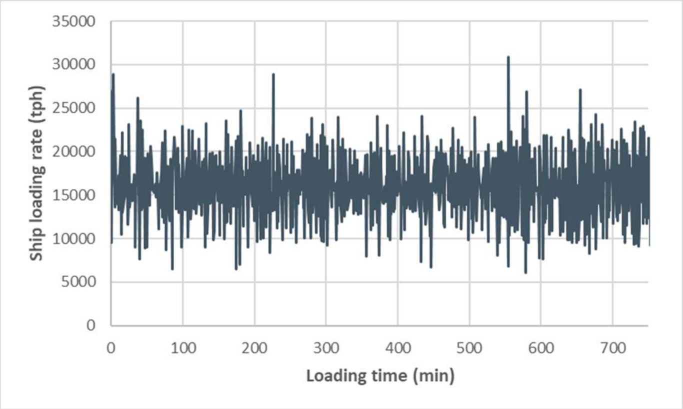
Figure 10. Regularization simulation with two simultaneous reclaimers: (a) Ship loading rate, (b) Bin inventory variation

From the graphs, it can be noticed that when only two reclaimers operate, the bin does not function as a buffer because, in general, the amount of material arriving at the bin is lower than the shipment capacity. As a consequence, the ship loading rate is still subject to high variations, with little or no regularization observed.

To address this issue, a new simulation was carried out considering three simultaneous reclaimers operating, to keep the bin at a high level. For this case, it was determined that the minimum capacity for the bin to be able to maintain a practically steady flow in the material reclaiming is 500 t. This value would accommodate reclaimer rate end-of-cone and end-of-pile fluctuations. However, due to equipment failures and as a safety measure, a 1,000 t capacity was adopted.

The regularized loading rate with three simultaneous reclaimers in operation is shown in Figure 11, alongside the inventory variation of the bin.

(a) (b)



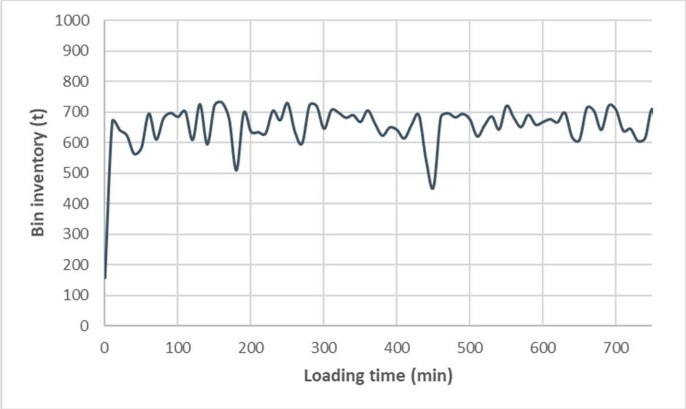


Figure 11. Regularization simulation with three simultaneous reclaimers: (a) Ship loading rate, (b) Bin inventory variation

The simulation showcased loading rates close to the nominal 16 ktph capacity, with a large reduction in the fluctuations observed in the base case (Figure 7), and elimination of downtimes with null loading rates. Effective loading time was reduced by 23%, which represents a 14% improvement in total time. The resulting annual shipment capacity increase is given in Table 5.

Table 5. Shipping capacity increase for shipment rate regulatization

Option	Description	Annual Shipping Capacity Increase
1	1,000 t capacity bin insertion	11.9%

4.4 Design improvement selection and implementation

A comparison of the three design improvements, in terms of shipping capacity increase, is provided in Table 6.

Table 6. Shipping capacity increases for all simulated design improvements

Design Improvement	**Option Description**	**Annual Shipping Capacity Increase**
Higher reclaiming capacity	Substitution of two existing 8 ktpa bucket reclaimers by two new 16 ktpa bucket reclaimers	3.1%
	Acquisition of one new 8 ktpa bucket reclaimer and one new 16 ktpa bucket reclaimer	0
	Acquisition of one new 8 ktpa bucket reclaimer and repowering of one existing 8 ktpa bucket reclaimer to reach new capacity of 12 ktpa	0
Higher ship loading capacity	Pier A ship loader repowering to 16 ktph	1.5%
	Pier B pier ship loader repowering to 16 ktph	2.3%
Shipment rate regularization	1,000 t capacity bin insertion	11.9%

With the highest improvement in terms of capacity increase, the shipping regularization solution was selected for implementation, involving the insertion of a 1,000 t bin and utilization of three simultaneous reclaimers. Besides the capacity increase, this design improvement also results in an optimization of the port terminal operations, reducing loading rate fluctuations and increasing flexibility to deal with equipment failures.

An available area between yards A and B was selected for later conceptual engineering development of the new regularization system.

5. CONCLUSIONS

The dynamic simulation model developed in Rockwell's Arena® software was calibrated by simulation of a base case, with very similar results in comparison to the real shipping. After calibration, the model was used to simulate the shipping operations of three scenarios, each one containing proposed design improvements: higher reclaiming capacity, higher ship loading capacity and shipment rate regularization. Showing the best results in terms of operations improvement, including a projected increase in annual exportation capacity of 11.9%, the shipment rate regularization solution was selected as the best option for implementation, with addition of a 1,000 t bin and operation of three simultaneous reclaimers. The dynamic simulation proved itself a valuable tool to evaluate the proposed design improvements in a risk-free environment, providing numerical data to each of the solutions and serving as the basis for the selection and dimensioning of the new equipment to be designed in the conceptual engineering phase.

6. REFERENCES

1. "Iron ore facts" [website]. *Natural Resources Canada*; 2022 [cited 2023 Jan 02]. Available at: https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/iron-ore-facts/20517.
2. "Iron ore" [website]. *Companhia Siderúrgica Nacional*; 2020 [cited 2023 Jan 02]. Available at: https://www.csn.com.br/en/homepage/iron-ore/#:~:text=Sinter%20Feed%20(6.3%20mm%20%2D%200.150,sinter%20feed%20usually%20exceeds%2063%25.
3. "Iron Ore Imports by Country Plus Average Prices" [website]. *World's Top Exports*; 2022 [cited 2023 Jan 02]. Available at: https://www.worldstopexports.com/iron-ore-imports-by-country/.
4. C. Comtois and B. Slack, "Dynamic determinants in global iron ore supply chain," *CIRRELT*, 2016.
5. Hatch Ltd. *Dynamic Simulation General Services*; 2020. Unpublished internal company document.