A multi-product mathematical model for iron ore stockyard planning problem

Um modelo matemático multiprodutos para o problema de planejamento de meios de ferro

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Marcos Wagner Jesus Servare Junior
Electrical Engineering Department
Instituição: Federal University of Espírito Santo
Endereço: Av. Fernando Ferrari, 514 - Goiabeiras, Vitória - ES
E-mail: marcoswjunior@gmail.com

Helder Roberto de Oliveira Rocha
Electrical Engineering Department
Instituição: Federal University of Espírito Santo
Endereço: Av. Fernando Ferrari, 514 - Goiabeiras, Vitória – ES
E-mail: helder.rocha@ufes.br

José Leandro Félix Salles
Electrical Engineering Department
Instituição: Federal University of Espírito Santo
Endereço: Av. Fernando Ferrari, 514 - Goiabeiras, Vitória - ES
E-mail: jleandro@ele.ufes.br

ABSTRACT
Stockyards in port areas are essential in supply chain management, due to the aggregation of logistical costs. Its objective is to carry out the ships' loading according to their capacity and specification of the iron ore characteristic. For solid bulks, product stockpiles are allocated along with the stockyards, together with the receiving and handling system, in addition to blending and recovering stockpiles for supplying ships. In the optimization of this system, some factors point to a variety of flows and products (types of iron ore) demanded, increasing the system's complexity. This paper aims to present a multi-product mathematical model from mixed-integer linear programming for allocating stockpiles with different mining resources, facilities, and equipment. Numerical results show a comparison of the computational efficiency of simulated instances with different numbers of equipment, minas, and ships using the commercial solution CPLEX.

Keywords: Iron Ore Stockyard Planning Problem, Mathematical Modeling, Stockyards Programming.

RESUMO
Pátios de estocagem em áreas portuárias são importantes na gestão da cadeia de suprimentos, devido a agregação de custos logísticos. O seu objetivo é realizar o carregamento dos navios de acordo com a sua capacidade, especificação da característica de minério e, ainda, da maneira mais rápida.
possible. For granular solids, there are allocations of product piles along the storage yards, along with the reception and movement system, as well as pile mixtures and recovery for ship replenishment. In optimizing this system, factors that indicate a variety of flows and products (types of ore) are demanded, increasing the complexity of the system. Therefore, this article aims to present a mathematical multi-product model for pile allocation with different ore characteristics, considering the equipment and installations used in this movement. Numerical results compare the computational efficiency of different instances using the commercial solver CPLEX.

**Keywords:** Problem of Stockyard Planning of Iron Ore Yard, Mathematical Modeling, Stockyard Programming.

**Topics (POI – PO in Industry, PM – Mathematical Programming and PO in Management and Production)**

**1 INTRODUCTION**

Brazil is an essentially mining-based country with a wide variety of mineral resources in its subsoil, many of them, on a large scale [Sakamoto et al. 2020]. In ports, stockyards are very important in the logistics chain to which they belong, influencing their performance [Servare Junior et al. 2018] significantly. Specifically, when it comes to solid bulk, such as coal and iron ore, the planning of allocation of the piles and sequencing of the use of resources directly impacts the performance of port processes. According to the seriousness of the situation, it may even interrupt the supply process for a period. Still, penalties may occur, for example, if a ship that has its departure delayed due to inefficiency in the process. Thus, it may result in a contractual fine from the vessel owner.

On the other hand, if the allocation is efficient, it will provide a higher capacity used of resources, lower costs, and a better overall result of this supply chain. However, due to the complexity of the production system and the required flexibility, using empirical methods does not guarantee an optimized system, generating costs and waste in the production process. An optimized solution can result in significant savings through better capacity utilization. In addition to this economic benefit, other considerations regarding the system must be used to ensure different situations related to the problem, such as reducing environmental impacts, energy costs, controlling violations of regulations, and using uncertainties, both in production and in customer orders.

Due to the wide range of production scheduling problems, several approaches have been developed. These include manual computer-supported programming (such as interactive Gantt chart), expert systems, mathematical programming (Linear Programming - LP, Mixed Integer Linear Programming - MILP - and Mixed Integer Nonlinear Programming - MINLP), various heuristics, evolutionary algorithms, and different artificial intelligence (AI) methods (see [Floudas and Lin 2004], [Méndez et al. 2006], [Li and Ierapetritou 2008a], [Li and Ierapetritou 2008b], [Ribas et al. 2010], [Phanden et al. 2011], [Maravelias 2012], [Lopes et al. 2018]).
An essential feature of this problem is that the space available in the stockyard can accommodate the ore batches arriving from the trains and allows for changes in alternative plans in the event of equipment failure, thus ensuring optimized planning of stockpiles in the stockyard.

In real situations, equipment or participants must be considered, such as the flow between the equipment, the amount of cargo loaded on the ships, and the number of ships served, increasing the complexity. Planning the stockyard-port system considering a variety of products is more complicated due to the inclusion of new demands and new flows.

Thus, this paper aims to present a mathematical model for an iron ore stockyard planning problem, its internal movement and supply with different types of iron ore, which seeks to maximize the number of ships in the planning horizon, thus approaching reality observed in companies. There are few problems discussed in the literature similar to the patio planning problem studied in this paper.

This paper was structured as follows: section 2 presents a literature review on the Stockyard Planning Problem. In section 3, a description of the problem and the mathematical model proposed in this work are presented. In section 4, the instances of this study are defined, as well as the results of experiments of the mixed integer linear programming model. Finally, section 5 presents the conclusions.

2 STOCKYARD PLANNING PROBLEM

Currently, the price of iron ore tends to remain at lower levels than those achieved in the recent past and a significant increase in the projected volume for the coming years with the minimum investment in new facilities. So, adequate stockyards management is essential to ensure a global performance balanced between costs, capacity, and productivity in the logistics chain. Thus, the demand for optimizing stockyards is no longer a possibility or study, but rather a requirement of mining companies to support the guideline of doing more with less.

In other words, the order in these times is to extract the maximum from the existing assets, thereby achieving better results without the need for expenditure on new equipment and installations. In this scenario, the use of optimization tools and techniques becomes an excellent option to generate low-cost solutions that are fully adequate to existing problems. In this section, we will review some works of Stockyard Planning Problem with different types of stockyards in the supply chain.

A solution to the stockyard planning problem is not trivial. It requires detailed research to identify alternatives technics which are effectiveness and have potential to be use. Given the degree
of complexity found, this problem can be classified as NP-hard, that is, those that require exponential time to obtain an optimal global solution [Voudouris 1997]. Thus, in addition to the search for the optimal solution, it is important to look for alternatives with good local solutions that can be used by stockyard operators and managers in the decision-making process.

According with [Menezes et al. 2017], the stockyard planning problem are optimization problems in a medium- and short-term horizon, considering the quantities to be produced, prices and demands, according to the achievement of goals defined by higher levels. The technique used by the authors to solve the problem was the Column Generation (CG) with Branch and Price.

In [Abdekhodaee et al. 2004] the analysis of the planning of a solid bulk stockyard is carried out for the coal chain in Australia, with a focus on train programming in which the two problems were separated into several modules, solving each of them through a greedy heuristic. [Boland et al. 2012] developed a coal stockyard planning technique based on a greedy heuristic improved with the use of the entire schedule in order to increase the flow of raw materials and decrease the average time of ships in the berth.

[Pimentel 2011] proposes a global approach to the optimization of the ore logistics chain, and the management of mine stockyards are performed in a simplified way disregarding the aspects of routes and equipment maintenance. In conjunction with the mathematical model, the Goal Programming approach proposed by [Ignizio, 1978] deal with the objective conflict aspect of each step or part of the process. [Almeida e Pimentel 2010] adopted a mixed integer programming model to solve the short-term scheduling problem of ore production, processing and shipping.

In [Nóbrega 1996] the problem from the point of view of the chain is also observed, being that in the stage of stockyards, only the stockpiles that are formed and recovered are addressed without concern for their location, dimensions or geometry. This author solves the problem using integer programming and linear programming.

[Bittencourt e Matede 2009] work in an analysis of steel coil storage stockyards in a simplified way, considering only the internal movements of coils and shapes resulting from the stacking of these products. This paper uses a differential evolution algorithm to solve the problem. [Amorim Júnior 2006], on the other hand, analyzes the storage of steel coils in order to accelerate the dispatch process carried out in a pre-established planning period.

[Lopes et al. 2018] presents a greedy construction to determine the flow, movement and direction of ships in each berth to determine where each ship will be served in order to minimize the maximum time for berth occupation, so that there is homogeneous berth occupation and meeting demand for berths of entire fleet in a minimum time.
Finally, [Servare Junior et al. 2018] present a mathematical model of mixed integer linear programming with bi-objective to determine the ships that will be served by each berth in a specific queue of customers. The authors of this paper use two objective function to evaluated the model behavior in the studied scenarios. In general, it was observed that due to their characteristics of the problem, the papers used mathematical modeling, heuristics and meta-heuristics as techniques for solving it.

3 MATHEMATICAL MODEL

In the stockyard-port system there are unloading terminals (car-dumpers), stockpiles, stackers, reclaimers and berths for ships. The studied system begins with the shipment of iron ore removed from the mines from railway lines. This material is transported to the unloading terminals where the wagons loaded with ores are turned to unload their contents on conveyor belts. Next, this material is transported to the stackers and then they are stacked in the stockyard.

In the stockyards, the iron ore is deposited in stockpiles, which are divided by separating positions in the stockyard for storage, as shown in Figure 1. The construction of all piles to serve a single vessel can take several days. A stockyard stockpile is reclaimed using a bucket wheel reclaimer and the recovered cargo is sent immediately to the ships.

The stackers and reclaimers move freely to meet positions and stockpiles in stockyards. For stackers and reclaimers to function properly, they must remain at a distance to avoid collisions.
In this work it is considered that the movement of the stackers and reclaimers are synchronized, disregarding the interference of each other in their operation.

For application purposes it is considered that throughout the entire process there are different products, according to the type of ore and each of these products is allocated in only one stockpile already determined. In this way, a product can only be directed to the patio that houses it. With an order placed, the movements of the iron ore are calculated and the trains sent loaded with the batches or wagons of ore to the unload terminals.

After the arrival of the ore batches at the terminals, the stackers transfer them to the stockyards, where they will remain at rest until the ship arrives at the berth. Next, an assignment for the first ships occurs given a set of vessels arriving at the port. A ship cannot reach the berth before its estimated time. The ship's loading time is directly proportional to the number of stockpiles recovered.

This paper's proposal considers one of the bi-objective models presented in [Servare Junior et al. 2018]. Besides, contributions include the variety of products between the stockpiles, even if the mining niche is iron ore. These differ according to the quality and purity required by customers, separated into products from possible classifications and diversities, and allocated in different stockpiles. The blend of the raw material from the mine composes each product.

Thus, based on the proposed problem definition and the relations shown in Figure 1, the sets, parameters and variables of the proposed model are described:

**Sets**
- $A$: Set of Mines
- $B$: Set of Car-Dumpers
- $C$: Set of Stackers, Pads Reclaimers and Products (Iron Ore Types)
- $D$: Set of Stockpiles
- $F$: Set of Berths
- $N$: Set of Ships

**Parameters**
- $Dem_n$: Total demand of ship $n$
- $D_{prod}^{c}_n$: Demand of Iron Ore Type $c$ by ship $n$
- $\tau^{f}_n$: Load time of ship $n$ in berth $f$
- $Tm^{f}_n$: Moving time of equipments to load the ship $n$ in berth $f$
- $Cap^{c}_c$: Capacity of stacker $c$
- $Capp^{c}_cd$: Capacity of stockpile $d$ in pad $c$
- $Capr^{c}_c$: Capacity of reclaimer $c$
According to the defined notation, follows we describe the proposed Mixed Integer Linear Programming (MILP) model.

**Objective:**
Maximize the number of served ships.

\[
Maximize \ Z = \sum_{f \in F} \sum_{n \in N} X^n_f
\]  

(1)

**Constraints:**

1. Related to the capacity limits of each equipment or space in the stockyard or port:

   \[
   \sum_{b \in B} P_{ab} \leq \text{Cap}_a \quad \forall \ a \in A
   \]  
   
   (2)

   \[
   \sum_{c \in C} Q_{bc} \leq \text{Cap}_c \quad \forall \ b \in B
   \]  
   
   (3)

   \[
   \sum_{d \in D} R_{cd} \leq \text{Cap}_d \quad \forall \ c \in C
   \]  
   
   (4)

   \[
   \sum_{a \in A} S_{ac} \leq \text{Cap}_e \quad \forall \ c \in C
   \]  
   
   (5)

   \[
   \sum_{c \in C} T_{cf} \leq \text{Cap}_f \quad \forall \ f \in F
   \]  
   
   (6)

2. Flow constraints that ensure that everything that arrives at equipment, station or stockpile will be the same as what leaves them:

   \[
   \sum_{a \in A} P_{ab} = \sum_{c \in C} Q_{bc} \quad \forall \ b \in B
   \]  
   
   (8)

   \[
   \sum_{b \in B} Q_{bc} = \sum_{d \in D} R_{cd} \quad \forall \ c \in C
   \]  
   
   (9)
9 It ensures the meeting demand for each product on each ship.

\[
\sum_{f \in F} T_{cf} = \sum_{f \in F} \sum_{n \in N} D_{prod} X_{fn} \quad \forall \quad c \in C
\]  

(13)

10 A constraint which guarantees that one berth for a maximum will serve the only one ship:

\[
\sum_{f \in F} X_{fn} \leq 1 \quad \forall \quad n \in N
\]  

(14)

11 Constraints of binary and bounds variables

\[
X_{fn} \in \{0,1\} \quad \forall \quad n \in N, \quad \forall \quad f \in F
\]

\[
P_{ab}, Q_{bc}, R_{cd}, S_{dc}, T_{cf}, T_{pf} \in R^+ \\
\forall a \in A, \forall b \in B, \forall c \in C, \forall d \in D, \forall f \in F
\]  

(15)

4 COMPUTATIONAL TESTS AND DISCUSSION

The verification and validation procedure of the proposed model was carried out from the commercial solver CPLEX [IBM 2012] using a 2.5 GHz Intel Core i5 with 4Gb of RAM. We use random values to define the demand for each ship and create simulated instances since real values were not available.

Tables 1 and 2, inform the parameters used and the sets of each instance created to compare them. Their maximum and minimum values were elaborated based on a uniform random interval. In turn, the instances were defined based on the size of the problem. By increasing the amount of equipment and possibilities of ships and berths for mooring, the complexity will be increased and can be an evaluation criterion until the size of instance that the methodology is usable.
Table 1 – Uniform distribution of model parameters for generating simulated instances

| Parameter                  | Min | Max |
|----------------------------|-----|-----|
| Demand                     | 4   | 9   |
| Demand of Product          | 0   | Demand |
| Capacity of Berth          | 100 | 200 |
| Capacity of Reclaimer      | 35  | 60  |
| Capacity of Stacker        | 25  | 60  |
| Capacity of Stockpile      | 1   | 2   |
| Capacity of Car-Dumper     | 40  | 60  |
| Capacity of Mine           | 150 | 200 |

Table 2 also shows the separation of instances into groups according to the size of the cases. In the first group, situations 1 to 5, the change in scenario focuses on the growth in the number of turners and the number of pads (products). In instances 6 to 10, which have more significant attributes, the variation occurs in the number of products available (increase in the number of mines) and increase in the size of the pads, as well as the number of ships that can be served by the system. Finally, in instances 11 to 15, the increase occurs in all sets so that it is possible to evaluate up to which instance and its size the model is capable of solving.

| Instance | A   | B   | C   | D   | F   | N   |
|----------|-----|-----|-----|-----|-----|-----|
| 1        | 1   | 1   | 1   | 10  | 1   | 10  |
| 2        | 1   | 2   | 2   | 10  | 1   | 10  |
| 3        | 1   | 5   | 2   | 10  | 1   | 10  |
| 4        | 1   | 5   | 10  | 1   | 10  |
| 5        | 2   | 10  | 10  | 1   | 10  |
| 6        | 3   | 10  | 10  | 15  | 1   | 15  |
| 7        | 8   | 15  | 10  | 20  | 1   | 20  |
| 8        | 10  | 15  | 10  | 30  | 1   | 50  |
| 9        | 10  | 15  | 10  | 30  | 2   | 50  |
| 10       | 10  | 15  | 10  | 50  | 2   | 80  |
| 11       | 10  | 15  | 10  | 50  | 8   | 100 |
| 12       | 10  | 20  | 10  | 50  | 10  | 100 |
| 13       | 15  | 20  | 10  | 50  | 15  | 100 |
| 14       | 20  | 20  | 15  | 75  | 20  | 150 |
| 15       | 25  | 20  | 20  | 75  | 20  | 200 |

Considering the expressions (1) - (16), the information contained in Tables 1 and 2 were used to implement the mathematical model. We generate data from a code developed in the Python programming language, in such a way that the CPLEX [IBM 2012] performs its reading to run the optimization of each instance.
Table 3 shows the computational results of the instances’ implementation. The computational effort is in seconds (or fraction of seconds) for the CPLEX solver [IBM 2012]

The objective function – OF indicates the number of ships that can be served in each instance.

| Instance | OF | Time (s) |
|----------|----|----------|
| 1        | 3  | 0.03     |
| 2        | 5  | 0.03     |
| 3        | 5  | 0.03     |
| 4        | 7  | 0.03     |
| 5        | 9  | 0.03     |
| 6        | 15 | 0.03     |
| 7        | 20 | 0.03     |
| 8        | 50 | 0.05     |
| 9        | 49 | 0.06     |
| 10       | 66 | 0.09     |
| 11       | 59 | 1.19     |
| 12       | 64 | 1.61     |
| 13       | 69 | 7.08     |
| 14       | 98 | 77.44    |
| 15       | -  | 329*     |

The mathematical model was sufficient to solve the problem optimally by CPLEX 12.5 [IBM 2012] in instances 1 to 14, considering a restricted planning horizon limited to the number of ships and equipment capacity. However, in real cases, a longer planning horizon and a higher number of vessels is necessary.

For instance 15, the commercial solver was unable to find a solution due to the overflow of memory. We recommend a more robust machine to obtain this solution or to apply other techniques that may indicate a solution to the problems for this case and for possibly even more complex instances.

As a form of representation, according to the characteristics presented in Tables 2 and 3, the diagram of the problem of Instance 3 is shown in Figure 2 and the solution found is shown in Figure 2.
More specifically, the solution of Instance 3 represents the movement of ore between the pads that shown in Figure 3. Thus, it is possible to observe the different stockpiles, their sizes and their flow.

The growth of the Objective Function (number of ships served) is due to the increase in the number of equipment, customer demand and/or product availability (mines), as well as a higher flow between the equipment. We observe that the tool execution time does not exceed 78 seconds in the instances that it was possible to find a solution.

We notice that the instance 14 (77.44 seconds) execution time is much longer than those measured in the first groups (instances 1 to 10). It is adequate time for decision making regarding the choice of services, handling, and ore flow between equipment since the supply and loading of a ship's holds can last for days.
The number of vessels served decreased in Instances 8 and 9. In principle, it is contrary to what we expect by providing another berth for serving ships. The cause of this variation was that instance 8 had a more significant number of vessels with lower demand; thus, more attended ships occur. The randomness of the data increased the model's size and, consequently, of its complexity showed that the model continued viable and maintaining its logical interactions.

In general, the use of mathematical modeling considers the possibility for the company to carry out planning and re-planning in a short time horizon. Thus, it has an optimal solution when occurring changes during a more extended period planning.

5 CONCLUSION

This paper studied the planning and scheduling of activities for a solid bulk stockyard-port system with iron ore types with different characteristics. We proposed a mixed integer linear programming model to solve this type of problem, with a configuration of equipment and approach that other authors had not considered.

The model also supports the planning of supply and loading of ships, directing them to the berths that will perform the services. We addressed variations between instances, with an increase in the number of origins (mines), destinations (ships), equipment, and stockyard size for the problem studied. We evaluated the performance of the exact technique by comparing these different sizes of instances.

In some cases (instances 1 to 14), commercial solvers like CPLEX 12.5 [IBM 2012] could solve the problem in a satisfactory computational time (effort), considering the complexity of the decision making. However, for the more significant instance (15), it can be solved using specific techniques since the CPLEX process was interrupted due to out of memory. In these cases, techniques such as heuristics and meta-heuristics will be indicated, or even use a computer with more memory and a more robust processor to provide adequate solutions.

Thus, this paper presented the mathematical model as a viable tool that helps the decision-making agent to quickly find an optimal solution with information about the stockyard-port system. Also, in the literature on stockyard planning problems, there are no studies with the same characteristics as this iron ore stockyard-port system.

Future research may be carried out to describe even more robust models that consider changing organizational objectives during the company's journey and considering essential characteristics such as inventory turnover and adding to the mixed model of iron ores of origin in the mine to form the different products (types of iron ore) in the stockyard. The investigation of
heuristics and metaheuristics such as Simulated Annealing or Genetic Algorithm, solve instance 15 and even higher is also desired

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