OPTIMIZING THE SCHEDULING OF TORPEDO CARS TO FEED STEELMAKING WITH HOT METAL[1]

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Abstract

In many situations found in practice torpedo cars are used to feed the steelmaking with the hot metal produced in the blast furnaces. A number of different torpedo cars with respective capacities and thermal performances must be scheduled, resulting in a difficult logistical problem. One has to jointly decide to which blast furnace and then to which run in the steelmaking a torpedo car shall be assigned. The problem is subject to operational constraints both on the blast furnace and on the steelmaking. Thermal performance of the operation is crucial, since it brings efficiency to the system. This article reports an optimization approach to deal with the scheduling of torpedo cars problem. The first phase consists of computing good estimations on the temperature losses. The second phase consists of developing a mathematical model for the problem. The optimization procedure is based on a branch-and-bound algorithm. The ideas and methods developed in this work were tested on real data scenarios.

Key words: Operational logistics; Scheduling; Optimization; Hot metal transportation.

OTIMIZAÇÃO DO SEQÜENCIAMENTO DE CARROS TORPEDO NO ABASTECIMENTO DA ACIARIA

Resumo

Em diversas situações práticas carros torpedo são utilizados no abastecimento da aciaria com gusa produzido nos alto-fornos. Carros com diferentes capacidades e eficiências térmicas devem ser seqüenciados, gerando num problema logísitico difícil em que se deve decidir conjuntamente em qual alto-forno cada carro deve ser alocado e qual ou quais corridas da aciaria o mesmo de cobrir. O problema está sujeito a restrições operacionais tanto na aciaria quanto nos alto-fornos. O desempenho térmico na operação é crucial, pois impacta na eficiência do sistema. Este artigo relata uma abordagem por otimização para o seqüenciamento dos carros torpedo. A primeira fase consiste em calcular boas estimativas para as perdas térmicas. A segunda fase consiste em desenvolver um modelo matemático para o problema. O procedimento de otimização é baseado num algoritmo do tipo branch-and-bound. As idéias e métodos desenvolvidos foram testados em cenários de dados reais.

Palavras-chave: Logística; Seqüenciamento; Otimização; Transporte de gusa.

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1 INTRODUCTION

The operational logistics to feed steelmaking with hot metal is a challenging problem. Pig iron is produced in blast furnaces, a continuous process occurring at the ironmaking facility. At the other side, steel is produced in batches at the steelmaking facility. In many practical situations the connection between the two facilities is made by torpedo cars. In these cases torpedo cars have to be fulfilled with the hot metal in the ironmaking facility, and then transported in order to feed one or more runs in the steelmaking facility. Because there may have more than one blast furnace with different production rates and torpedos cars with different capacities, the decision on the order in which torpedos must be assigned to blast furnaces to feed the steelmaking is a complex scheduling optimization problem. (The reader is referred to Blazewicz et al.(1) for a comprehensive treatment of scheduling problems in manufacturing.)

The critical point in this logistic operation is the temperature losses, mainly when the torpedo cars are filled and waiting to be used in the steelmaking. Thus, management decision shall objective to minimize temperature losses, making possible the increase of the solid charge fraction resulting in more steel per hot metal produced per heat. Given (*i*) a number of torpedo cars with respective capacities and (*ii*) a sequence of runs in the steelmaking, the scheduling of torpedo cars problem consists of jointly deciding to which blast furnace and then to which run in the steelmaking a torpedo car shall be assigned. This problem is subject to operational constraints both on the blast furnace and on the steelmaking.

The article is organized as follows. The next section presents the method to compute estimations on the temperature losses of the hot metal in a torpedo car. It is a first step in addressing the scheduling of torpedo cars problem, since an estimation of temperature losses is needed when planning scheduling to a horizon ahead. Section 3 describes the optimization procedure developed to approach the scheduling of torpedo cars problem. Operations research, a quantitative methodology in engineering, was used to address the optimization problem, see for instance Hillier and Lieberman.(2) Final comments are made in the last section. The ideas and methods developed in this work have been tested in practice and they are in course of implementation in a major steel manufacturing industry in Brazil.

2 TEMPERATURE LOSSES

The practical situation studied is characterized by a number of different torpedo cars, both in capacity and design. Therefore, design parameters of each torpedo car had to be taken into account in computing estimations on the temperature losses over time of the hot metal. The energy equation is simplified version of the well-known Navier-Stokes considering just heat transfer. It can be written as

$$m \cdot cp \cdot dT/dt = \Sigma\, \ddot{E}$$

where m is the mass of hot metal, cp is the constant pressure specific heat, $\ddot{E}$ is the total energy variation, and T is the average temperature of the hot metal in the torpedo car. The right hand side is composed by two terms, the radiative thermal loss and the convective thermal loss, yielding

$$m \cdot cp \cdot dT/dt = \sigma \cdot A\,(T^4 - T\infty) + h_c \cdot A\,(T - T_w)$$

where A is the considered transfer area, σ is the Boltzmann number, and h_c is the coeficient of the free convection. To solve the resulting ordinary non linear differential equation the 4th order Runge-Kutta method(3) was implemented in C++.

2.1 Empirical Experiments

With the energy equation in hand, it has been possible to compute estimation on temperature losses for each kind of torpedo car available in the practical situation. It was observed that different torpedo cars have quite different thermal performances. Figure 1 shows the heat flow per ton for two specific torpedo cars: TC – Worse, the car having the higher rate of heat flow; and TC – Best, the car having the lower rate of heat flow. The heat flow per ton allows a comparison between different torpedo cars that is independent of mass, i.e., independent of the quantity of hot metal that a torpedo car can carry. Having knowledge about the differences in thermal performance of different cars is important when scheduling torpedo cars to feed the steelmaking. It is worth mention that in the practical situation the torpedo cars remain open while waiting to be used in the steelmaking.

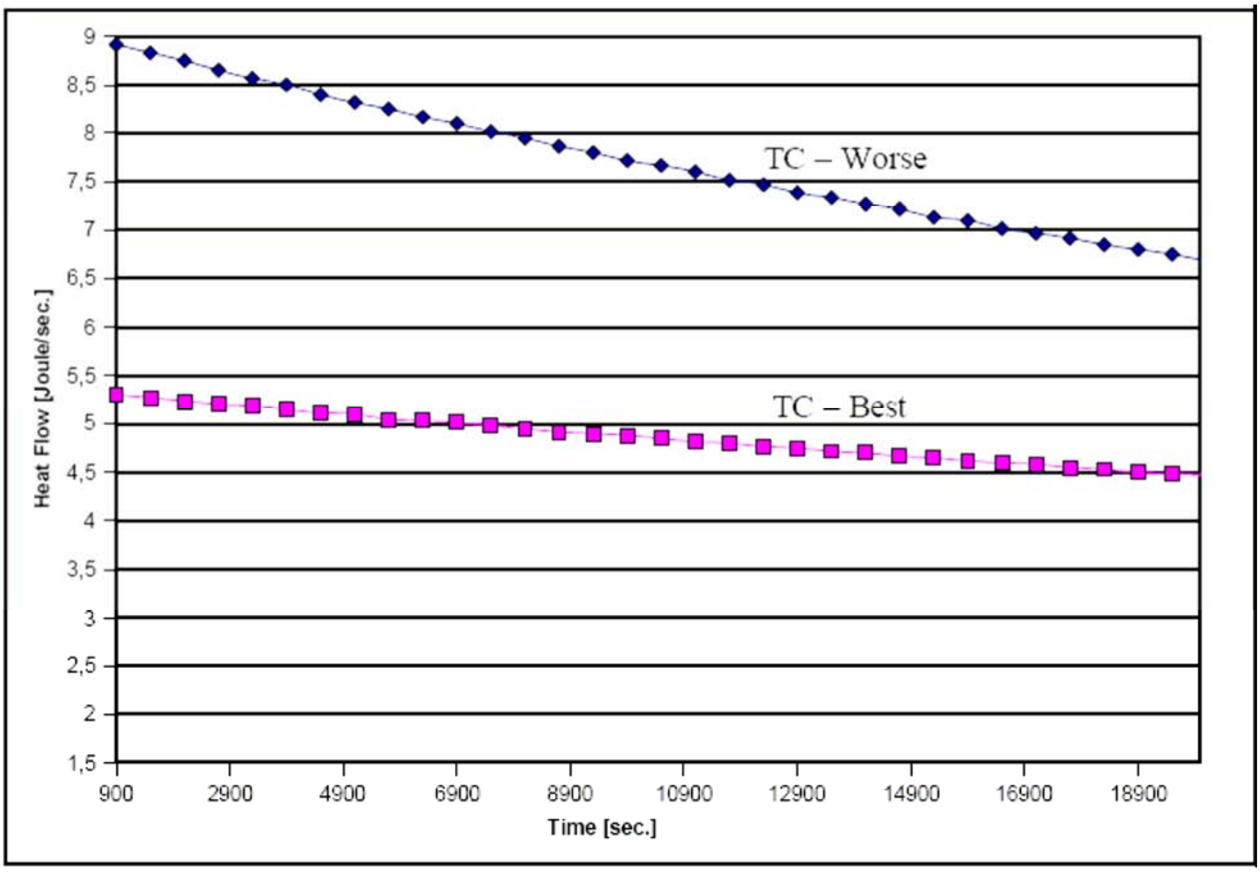

Figure 1. Heat flow per ton rates for two torpedo cars – the open cars actual situation.

The computation of estimations on the temperature losses were submitted to validation process. An experimental plan has been drawn in order to confront the computed estimations with actual temperature measures obtained on the operational area. Figure 2 shows relative percentual deviation between computed estimations and measures obtained. Torpedo cars been fulfilled in two different blast furnaces were considered. In Figure 2, BF 1 (resp. BF 2) indicates relative deviation for experiments on torpedo cars fulfilled on blast furnace 1 (resp. blast furnace 2). Results have validated the application of the method, since the maximum deviation observed was 6% and the literature considers acceptable a deviation around 10%, see Incropera et al.(4)

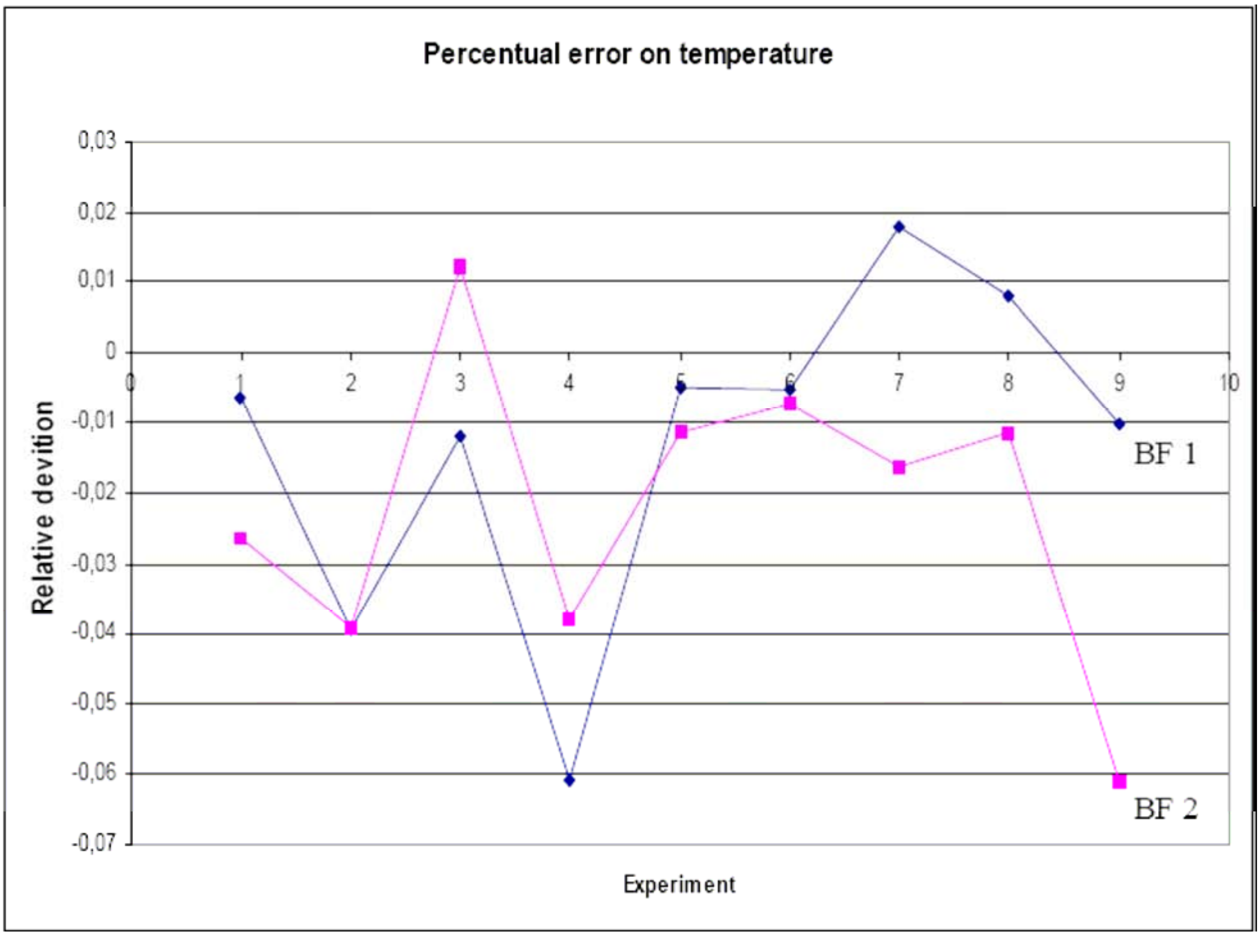

Figure 2. Results of the validation process comparing computed estimation with measured temperatures.

2.2 Scenario with Closed Torpedo Cars

With the purpose of increasing thermal performance of the torpedo cars, it has been studied a scenario where the cars remain closed while waiting to be used in the steelmaking. This would almost eliminate the radiative thermal loss, significantly reducing the heat flow transfer per ton rate. Figure 3 illustrates computation of heat flow per ton considering a scenario of closed torpedo cars. As it can be seen the closing the torpedo cars can be an improving course of action to increase thermal performance of the logistic operation, since, closed, the worse torpedo car would have a rate of heat flow significantly lower than actually observed even for the best torpedo car.

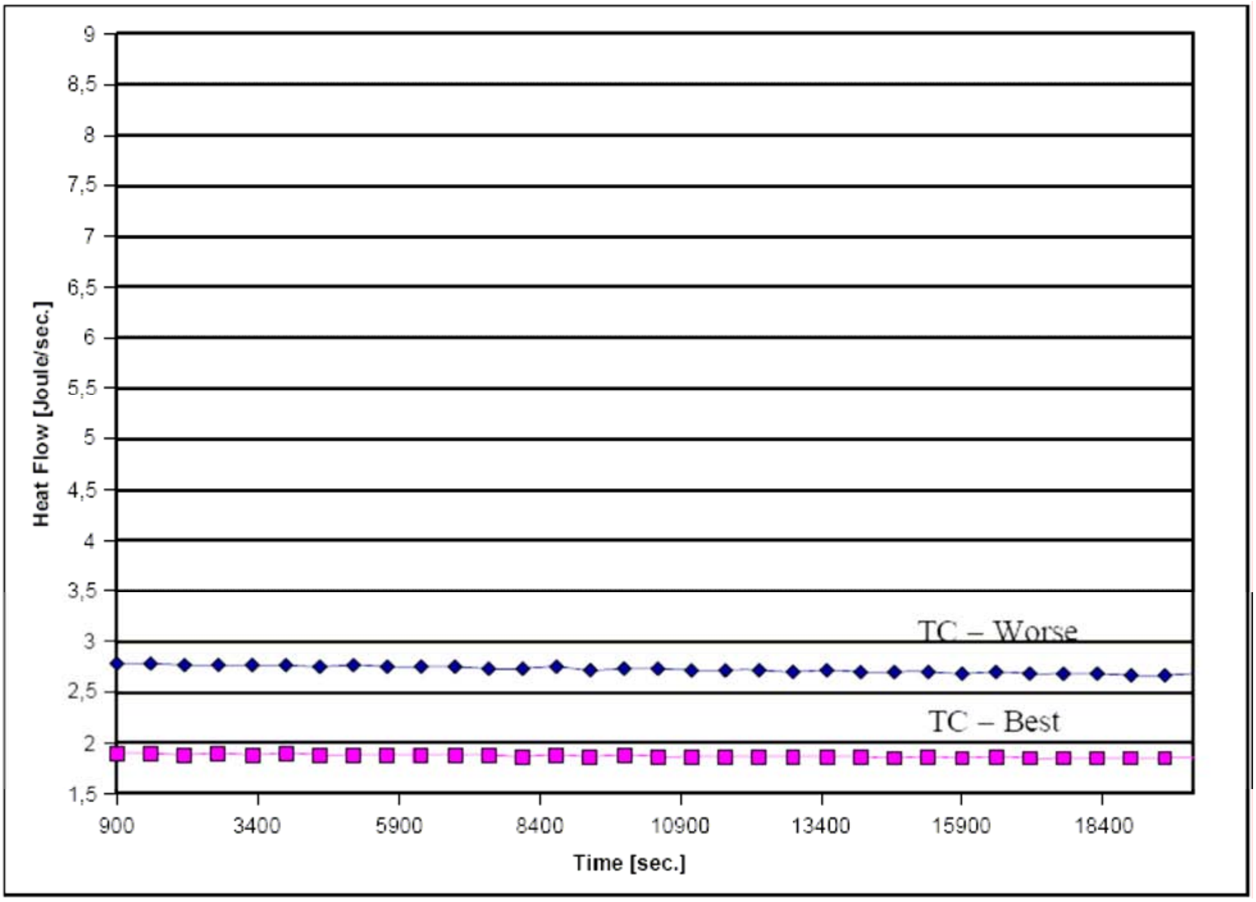

Figure 3. Heat flow per ton rates for two torpedo cars – the closed cars scenario.

3 OPTIMIZATION PROCEDURE

The optimization approach employs a mathematical model to find among alternative feasible solutions for a certain problem the best according to an evaluation criteria. Model-building is the essence of the optimization approach to management problems. One has to define (*i*) on what decision variables concern; (*ii*) an evaluation criteria for alternative feasible solutions based on measurable quantities; (*iii*) parameters which have to be considered; and (*iv*) constraints representing physical and logical relationships between the problem elements.

Decision Variables: Decision is modeled by employing binary variables. There is one binary decision variable for each triple < torpedo car – steelmaking run – blast furnace >. Thus, given J torpedo cars available for the logistic operation, P runs in the steelmaking that have to be fed with hot metal, and Q blast furnaces, the problem has $J \cdot P \cdot Q$ binary variables. A variable x_{jpq}, $j = 1,...,J$; $p = 1,...,P$; $q = 1,...,Q$; assumes value 1 if torpedo car j, must cover steelmaking run indexed by p, fulfilled in blast furnace identified by q, and assumes value 0 otherwise.

Control Variables: Control variables are needed to verify whether a configuration of the decision variables leads to a feasible solution in practice. There are two groups of control variables, both of them continuous. The first group is T_{jp}, $j = 1,...,J$; $p = 1,...,P$; which gives the temperature estimation of hot metal in torpedo car j at the moment to be used in steelmaking run p. The second is r_{jpq}, $j = 1,...,J$; $p = 1,...,P$; $q = 1,...,Q$; which controls the moment that torpedo car j must be started to be fulfilled in blast furnace q in order to cover steelmaking run p.

Evaluation Criteria: The objective is to maximize the temperature with which hot metal is used to feed the steelmaking runs. As mentioned above this is a measurable quantitative criteria, since temperature estimations are computed as control variables for a given feasible decision variables configuration.

Parameters: Several parameters are considered as input data in the optimization procedure. It is worth to mention some of them in particular. As the procedure is to decide the scheduling of torpedo cars to feed the steelmaking within a horizon of P runs, an input parameter is the moment which a steelmaking run p starts. Considering the blast furnace, important parameters are the production rate of each blast furnace q, and also the minimum and maximum time that blast furnace q shall be closed between fulfilling two subsequent torpedo cars.

Constraints: The scheduling of topedo cars is a challenging problem because it has operational constraints on both sides – constraints on the steelmaking and constraints on the blast furnaces. These operational constraints are characterized by the so-called time windows. On the steelmaking there must have a torpedo car with hot metal at the exact moment to start a run. But the torpedo car cannot be ready much earlier, for the cooling of the hot metal over time. So, the picture is worse than traditional manufacturing where only costs are incurred for holding work-in-process, since, besides costs, holding work-in-process degrades the thermal condition of the hot metal. On the other side, there are rigid time windows in the blast furnace. Once a torpedo car is fulfilled, there are limits on the minimum and on the maximum time that the blast furnace must be closed. For instance, no less than 25 or 30 minutes and no more than one hour. These constraints impose rigid time windows to assign another torpedo car to the blast furnace, complicating the matter.

Procedure Outline: The problem was modeled using a mixed integer programming formulation, and solved with techniques based on linear programming, see Johnson et al.(5) Input data for a planning horizon about 30 steelmaking runs are read from data base systems. Then, a branch-and-bound optimization algorithm(5) examines feasible solutions for the problem until conclude with an optimal solution. According to the values obtained for the decision variables, the outputs are (*i*) which torpedo car, and in which order, shall be assigned to each blast furnace; (*ii*) the moment to fulfill each torpedo car in each blast furnace; and (*iii*) which steelmaking run shall be covered by each torpedo car. Figure 4 shows the screenshot for an illustrative scenario based on real data. Output is displayed as a Gantt chart, providing decision support to the operations management. The different torpedo cars are identified by different colors. In the line associated to each blast furnace it is indicated the order to schedule the torpedo cars, and in the line associated to the steelmaking it is indicated the torpedo car to cover each run.

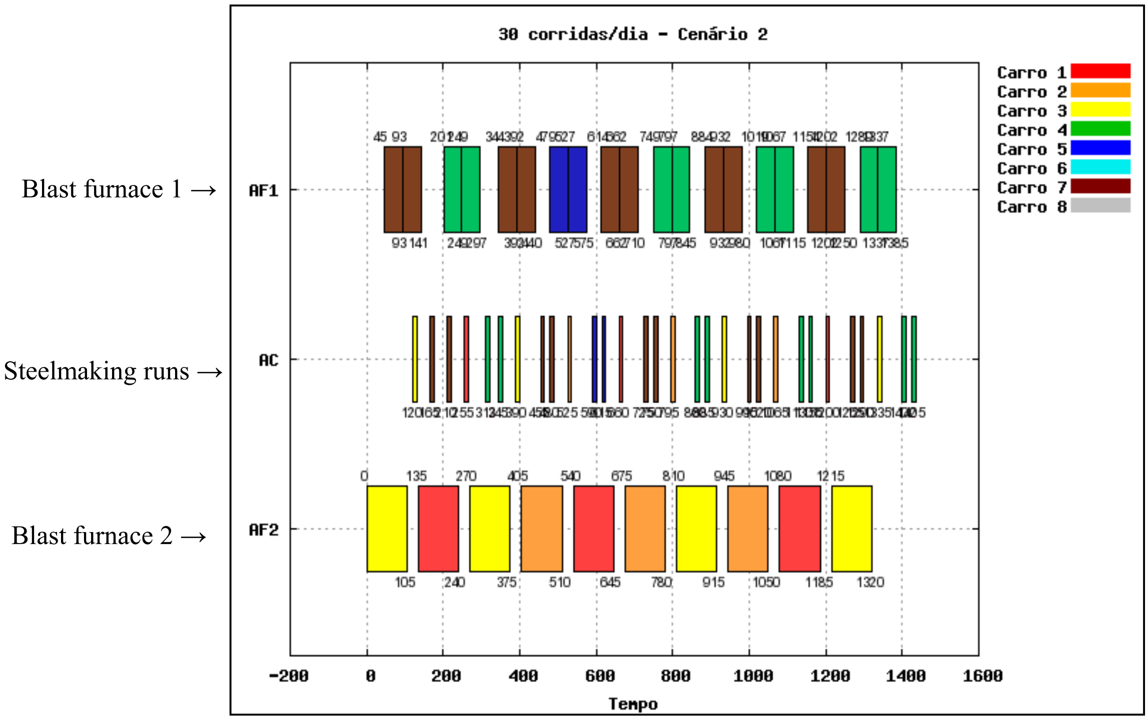

Figure 4: Screenshot of the optimization procedure, outpu as a Gantt chart for a real data based scenario.

4 CONCLUSIONS

This article presents methods developed to tackle a difficult problem in operational logistics. The thermal performance of the operation is crucial, since it brings efficiency to the whole system. Thus, a first phase in approaching the problem was computing good estimations on the temperature losses, to allow planning for a horizon of steelmaking runs ahead. Empirical experiments have shown that the numerical solution computed by Runge-Kutta method is a good estimation on the temperature losses, since estimations have presented a maximum deviation from measured temperatures of 6%. Additionally, studies on a scenario with closed torpedo cars have shown an improvement in thermal performance due to the elimination of radiative thermal losses. Indeed, in a scenario with closed torpedo cars, the worse torpedo car would have a rate of heat flow significantly lower than actually observed even for the best torpedo car. In a second phase, a mathematical model of the problem was developed. Computational experiments with the optimization procedure have shown two main advantages: (*i*) it has increased the temperature of the hot metal with which the torpedo car is used to supply the steelmaking, and (*ii*) it has scheduled the torpedo cars to cover the complete demand of hot metal for a fixed number of runs, reducing the number of torpedo cars held in process. The ideas and methods developed in this work were tested on real data scenarios and are currently under implementation in a major steel manufacturing industry in Brazil.

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