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Optimal scrap combination for steel production

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Abstract. In steel production, scrap metal is used for cooling the enormous quantity of heat produced by blowing oxygen on hot metal. Scrap differs in regard to the content of iron and of some tramp elements. The price of the scrap depends on these attributes. Each melting bath unit of steel has its own material constraints for the amount of iron and tramp elements in order to guarantee the desired quality. In addition, the transportation of scrap is restricted because it needs time and space: the scrap is kept in some railroad cars in the scrap hall; empty cars must leave the hall, filled cars must be taken from several railroad tracks in the scrap yard and assembled to a train before transportation to the hall. There are upper limits for the number of cars in the hall and in the train, also for the number of railroad tracks used for assembly.

Our objective is to find a minimum cost scrap combination for each melting bath unit of steel that obeys the material and transportation constraints. We model the problem using a MIP (mixed integer linear programming) approach. Real-life situations are solved with the commercial MIP-solver CPLEX. We present computational results which show significant improvement compared to the strategy applied today.

Zusammenfassung. In der Stahlproduktion wird zur Kühlung des flüssigen Roheisens Metallschrott hinzugefügt. Dabei wird Schrott mit unterschiedlichem Gehalt an Eisen sowie an Spurenelementen eingesetzt. Abhängig von dieser Zusammensetzung variiert der Einkaufspreis für den Schrott. Für jeden produzierten Stahltyp sind gewisse Grenzwerte für Eisenanteil und den Gehalt an Spurenelementen im Stahl einzuhalten, um die geforderte Qualität zu erreichen. Der Schrott wird in Eisenbahnwaggons gelagert. Dadurch, daß Züge aus diesen Waggons gebildet werden müssen und diese Züge die Werkshalle auf dem vorgegebenen Gleisnetz erreichen bzw. verlassen müssen, entstehen zusätzlich zu den Materialrestriktionen auch noch Transportrestriktionen.

Unser Ziel ist es, für jeden Produktionsprozeß die kostengünstigste Schrottzusammenstellung zu finden, so daß alle Material- und Transportrestriktionen eingehalten werden. Wir modellieren das Problem mit Hilfe eines gemischt-ganzzahligen linearen Programms (MIP) und lösen es mit dem kommerziellen MIP-Löser CPLEX. Unsere Rechenergebnisse für reale Produktionsserien zeigen bemerkenswerte Einsparungen gegenüber dem zur Zeit verwendeten Verfahren.

Key words: Mixed integer programming – Steel production

Schlüsselwörter: Gemischt-ganzzahlige lineare Programmierung – Stahlproduktion

1 Problem

Situation

Hüttenwerke Krupp Mannesmann (HKM) produce slabs and round bars by casting about 60 melting bath units of steel per day. There are more than 1,500 different steel types according to the various purposes of subsequent treatments. Therefore, each melting bath unit has its own lower and/or upper limits for the chemical composition with regard to more than 30 elements, especially the tramp elements copper (Cu), chrome (Cr), nickel (Ni), molybdenum (Mo), and tin (Sn).

Each melting bath unit, further on called "process", is produced in one of the two so-called "converters" by blowing more than 10,000 m^3 oxygen on about 200 t of hot metal within less than 20 minutes. The hot metal, supplied from the blast furnaces, has a temperature of at least 1,300°C. The carbon in the hot metal and the oxygen burn to a gas (CO), which leaves the converter. This oxidation produces an enormous quantity of heat, resulting in a heating up of more than 600°C. A computer model calculates the particular temperature needed at the end of the blowing process in order to avoid problems with the temperature during the casting process starting 60–120 minutes later. This particular temperature ranges between 1,600 and 1,800°C. In order to meet the desired temperature, before the liquid steel is tapped into a ladle, the oxidation heat must be reduced by

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using scrap metal and iron ore. Metallurgical models calculate the particular amount of scrap and iron ore needed for cooling for up to 30 charges in advance. The amount of scrap ranges between 25 and 90 t for each process.

Scrap is a valuable material and costs much more than iron ore. The carloads come from different sources:

- some are collected as residuary products in HKM's own production process, for example at the casting machines and in the finishing shop,
- some are obtained as waste products from other companies of the steel industry, e.g. rolling mills,
- some are bought from scrap dealers, who got the scrap by the demolition of halls and machines.

The received scrap is divided into several classes, called A, B, C and so on. All classes are assumed to have the same cooling effect (at the moment), but different relative iron and tramp element amounts, and prices. The cheaper scrap has a low content of iron and/or high content of tramp elements. For most charges the cheapest scrap does not comply to the upper limits for the chemical composition, so that another scrap class or a combination of different scrap classes must be used. For some classes, the chemical behavior during the blowing process is especially difficult to handle, so that only few tons of them may be chosen.

Scrap can be substituted by a mixture of iron ore and additional hot metal, because one unit of iron ore and three units of hot metal have the same cooling effect as four units of scrap. As this substitution leads to about 10% less amount of iron, the formula must be multiplied by 1.1. For example, 3.3 t of iron ore and 9.9 t of hot metal can be chosen instead of 12 t of scrap. The substitution is limited by a maximum of 9 t of iron ore, because iron ore must be added in small portions during the blowing process.

Scrap must completely be filled in the converter ahead of the hot metal. For each charge it is supplied from the scrap hall by using cranes and transport containers. In the hall, the scrap is kept in railroad cars on two tracks. When all cars on one track are empty, a transport company is under contract to remove the cars and to fetch new filled cars from several parallel railroad tracks at the scrap yard. This situation happens every 90–180 minutes. Before transportation to the hall the filled cars must be assembled to a train, whose length must comply to the capacity of the hall. That is why a train must not exceed 8 cars. On the other hand, transportation needs so much time that the maximum number of cars is desired in order to ensure the supply.

Each filled car at the scrap yard contains between 30 and 50 t of one particular class of scrap. For each train the cars have to be chosen according to the planned production program and the suitable classes of scrap. They may be located on several tracks, but the locomotive can only work on up to three tracks. The tracks are divided into "single-class" and "multi-class". On single-class tracks, all cars contain scrap of the same class. From these, cars may be selected only from the front, whereas those from the multi-class tracks may be selected from any position. These transportation constraints must be obeyed in order to guarantee that the train will arrive at the hall in time.

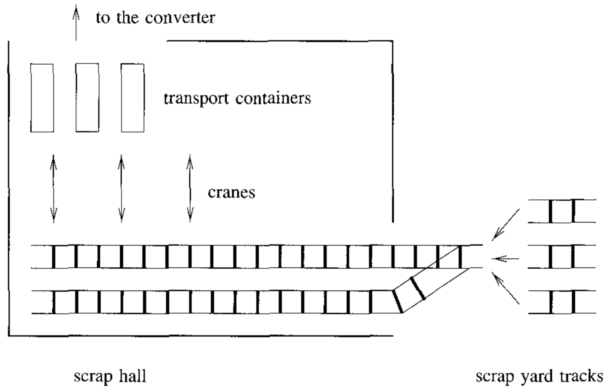

Fig. 1. Scrap hall and scrap yard

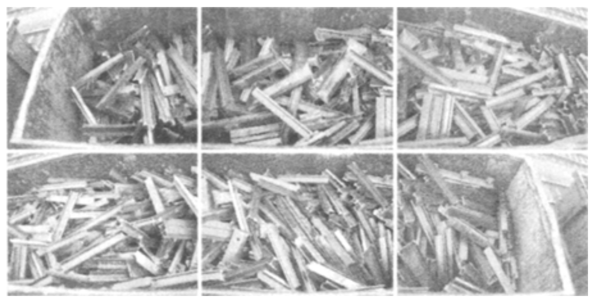

Fig. 2. Railroad cars containing scrap

Operations

Steel is produced day and night, even at weekends. Therefore one of the so-called "scrap dispatchers" must take care that the scrap needed for each process is available without delay at any time. The scrap dispatcher works in a control post in the scrap hall and has to execute three main operations:

- check the cars coming to the scrap yard and determine the scrap class for each car,
- decide when the transport company has to fetch new filled cars from the scrap yard and which cars shall be assembled to a train,
- decide when and how much scrap of the different classes in the hall has to be filled into the transport containers for each charge.

A camera takes several pictures of each car before it arrives at the scrap yard. At the same time the dispatcher can see the pictures on a monitor, judge the scrap and thus implement the quality control. Scrap not matching the order is sent back to the supplier.

An information system shows the scrap supply, i.e. all cars, located in the hall or at the scrap yard, including their positions, classes and amounts of scrap. This is shown in Fig. 3: There are three columns for each track indicating car number, scrap class and scrap amount. As one can see, there are tracks containing one class of scrap whereas other tracks contain different classes.

Also, the information system shows the scrap demand, i.e. all initiations of blowing processes, planned in the future production schedule, including the particular kind of

```
S651 HARF 4 1 . .......  Waggons in der Gleisharfe   250  20.01 12:46 03/04
letzte Aktualisierung: 20.01 11:54                                     01/01
G5022 0724to G5024 0676to G5025 0381to G5026 0896to G5027 0403to G6003 0367to
WNR  Klas to WNR  Klas to WNR  Klas to WNR  Klas to WNR  Klas to WNR  Klas to
5524 C198 39 9869 C197 41 1298 W199 56 9494 C197 47 6561 C197 37 0340 C199 82
7339 C198 40 0902 C197 38 2987 W199 57 7118 C197 44 4498 C197 53 1773 C198 57
3288 C197 43 7030 C197 38 7338 B199 51 4468 C197 41 7416 C197 52 2616 C198 55
0386 C197 48 8349 C197 40 0493 B199 59 1417 C197 49 0810 C197 45 1752 C197 23
2543 C197 53 1483 C197 36 0886 D197 42 1652 C197 43 0650 C197 43 2879 C197 42
4799 C197 49 2342 C197 46 1661 D197 41 5718 A199 45 2770 C197 38 5106 C198 54
8655 C198 24 9658 C197 42 1756 D197 34 3313 Y198 27 4132 C197 32 4782 C199 54
0517 C198 28 8696 C197 39 4080 D197 42 6599 C197 56 5055 C197 38
2389 C197 30 8366 C197 36              6599 C197 56 5055 C197 38
0498 C198 50 1605 C197 35              1586 C197 59 0079 C197 32
0602 C197 28 9665 C197 36              4842 C197 51
1707 C198 28 9287 C197 33              8587 C197 57
8752 C198 58 0911 C197 33              7064 C197 56
1157 C198 57 7233 C197 32              1806 C197 58
5929 C198 49 0029 C197 32              1222 C197 51
9139 C197 34 8258 C197 30              3216 C197 57
8965 C197 36 6327 C197 34              4321 C197 51
0953 C198 31 4173 C198 55              0209 C197 52
```

Fig. 3. Screenshot of a part of the scrap yard

steel type, the calculated amount of hot metal and cooling material, and a recommended scrap class combination (cf. Fig. 4). Every line corresponds to one process. The first two coluns show the number of the used converter and a process identification number. The column entitled "Guete" holds a character determining the steel type (and therefore the material constraints), the columns "Aufteilung in Schrottklasse/Menge" represent the scrap combination recommendation.

Optimization

At the moment, there is a simple strategy (henceforth named *HKM heuristic*) to determine the recommendation: for each steel type, one of eight different predetermined scrap class combinations is chosen by rules regarding the material constraints. The scrap supply and the transport constraints are completely ignored. Therefore, the dispatcher often has to deviate from the recommendation, if a particular scrap class is not available at the scrap yard or is blocked due to the transport constraints.

If the assembly of a train with cars containing scrap combinations proposed by the HKM heuristic is impossible, the scrap dispatcher has to decide for an alternative scrap combination, which generally results in scrap of higher quality but also higher cost. Since there is no time for complex calculations at that moment, the quality and the cost of a chosen scrap combination depend on the personal experience of the dispatcher. An analysis of this partially manual process yields the option of a significant reduction of costs.

Therefore, HKM aims at solving the following optimization problem:

Find a minimal cost combination of scrap classes and iron ore for the next 5–8 blowing processes, starting with the first process which must be supplied from the scrap yard. The combination must satisfy the following constraints:

- the calculated cooling effect for each process is ensured,
- the material constraints for each process are not violated,
- the transport constraints for each train are obeyed.

Since every 20–25 minutes a process is started at a converter, 5–8 charges represent 100–200 minutes production time. This is called a *process series* in the sequel.

```
S631......................  Schrott-Disposition:   150  20.01 12:45 01/02
      SEP: 12:43      SRD-Nah: 12:44    SRD-Fern: 12:44
K PLANR Guete  BBEG 1.R.Esto Aufteilung in Schrottklasse/Menge:
2 94417 V13MNC 13:07 237 56E C... 46 D... 09 L... 02 .... .. .... ..
1 33860 P40MNC 13:26 236 69E C... 68 L... 02 .... .. .... .. .... ..
2 88633 S30/D7 13:46 235 77  C... 62 Y... 15 .... .. .... .. .... ..
1 27292 S35/ 1 14:05 236 72  C... 72 .... .. .... .. .... .. .... ..
2 33878 P40MNC 14:36 236 73  C... 72 L... 02 .... .. .... .. .... ..
1 88641 S30/d7 14:55 235 80  C... 64 Y... 16 .... .. .... .. .... ..
2 93716 C67/ 3 15:14 234 62  B... 62 .... .. .... .. .... .. .... ..
1 88658 S30/D7 15:33 235 81  C... 64 Y... 16 .... .. .... .. .... ..
2 27300 S35/ 1 15:52 236 76  C... 76 .... .. .... .. .... .. .... ..
1 33886 P40MNC 16:12 236 69  C... 68 L... 02 .... .. .... .. .... ..
2 88666 S30/D7 16:31 235 79  C... 63 Y... 16 .... .. .... .. .... ..
1 93724 C67/ 3 16:51 234 64  B... 64 .... .. .... .. .... .. .... ..
2 88674 S37/M3 17:15 237 79  C... 63 D... 16 .... .. .... .. .... ..
1 27318 S35/ 1 17:34 236 74  C... 74 .... .. .... .. .... .. .... ..
2 93732 C67/ 3 18:31 234 64  B... 64 .... .. .... .. .... .. .... ..
1 33613 F36/ 3 19:19 237 69  C... 56 D... 14 .... .. .... .. .... ..
2 27375 V25CRM 20:17 238 66  D... 61 L... 05 .... .. .... .. .... ..
1 33621 F36/ 3 20:51 237 72  C... 57 D... 14 .... .. .... .. .... ..
2 65896 F47/ 6 21:38 234 65  B... 63 L... 02 .... .. .... .. .... ..
1 27383 S52S/  21:57 237 69  C... 55 D... 14 .... .. .... .. .... ..
```

Fig. 4. Screenshot of the planned converter processes

The optimization result is needed within 20 seconds in order to meet a total response time of the whole information system, which will be accepted by the dispatcher.

2 Constraints

A process requires a particular amount of cooling material. Cooling material consists of scrap and a combination of iron ore and hot metal according to the substitution formula.

Cooling effect constraints

For each process:

- the cooling material must meet the calculated cooling effect, expressed in scrap units,
- if iron ore is chosen instead of scrap, the cooling material must obey the substitution formula: 1.1 unit of iron ore + 3.3 units of hot metal = 4 units of scrap.

Material constraints

For each process:

- the relative amount of the tramp element Cr in the produced steel must not exceed a given level (the same for Cu, Ni, Mo and Sn). The loss of parts of the input tramp elements due to oxidation during the process is reflected by a so called *output factor*, expressing the relative amount that remains,
- the relative amount of iron (Fe) in the produced steel must observe a given lower limit,
- the amount of iron ore must not exceed the given upper limit of 9 t,
- the amount of scrap for each class must not exceed a given upper limit.

Transportation constraints

For each train from the scrap yard to the hall:

- up to eight cars may be used,
- cars may be assembled from three tracks or less,
- cars in single-class tracks may be selected only from the front.

3 Model

In order to solve the problem of finding a minimum cost scrap and iron ore combination, we use a *mixed integer linear programming* model (MIP).

Our model determines the minimum cost combination based on material costs while ignoring the transport costs. Continuous variables will determine the scrap, iron ore and additional hot metal amount while binary variables will give the decision which cars to take from the scrap yard.

Small (Roman or German) letters are used for indices and variables, capital letters for constants.

Constants

The following constants influence the optimization (to simplify our exposition, we only mention chrome (Cr) as tramp element, there are equivalent constraints for other elements like Cu, Mo, Ni, Sn):

K	number of processes for the train
G	number of tracks on the scrap yard
Z_g	number of cars on track g
$\mathfrak{K}$	set of all scrap classes
$\mathfrak{K}_{\mathfrak{g},\mathfrak{p}}$	class of scrap in car p of track g
$M_{g,p}$	scrap amount in car p of track g
J_k	desired cooling effect (in scrap units) of process k
R_k	initial hot metal amount for process k (this has to be distinguished from the *additional* hot metal amount that is to be determined by our model)
$P_\mathfrak{k}$	price of 1 t of scrap of class $\mathfrak{k}$ (also: P_E for iron ore, P_R for hot metal)
$\mathrm{Cr}_\mathfrak{k}$	relative amount of Cr in scrap of class $\mathfrak{k}$ (also: Cr_E for iron ore, Cr_R for hot metal)
A_{Cr}	output factor of Cr
$\overline{\mathrm{Cr}}_k$	maximum allowed relative amount of Cr in the steel produced in process k
$\underline{\mathrm{Fe}}_k$	minimum required relative amount of Fe in the steel produced in process k
$\overline{N}_\mathfrak{k}$	maximum allowed absolute amount of scrap of class $\mathfrak{k}$ in one process

Variables

$x_{g,p,k}$	scrap amount from track g, car p for process k
e_k	iron ore amount for process k
r_k	additional hot metal amount for process k
$w_{g,p}$	(binary) indicator that car p from track g is used for the train
s_g	(binary) indicator that track g is used for the train

Constraints

When describing the model constraints, we will use $\sum_{g,p}$ as an abbreviation for $\sum_{g=1}^{G}\sum_{p=1}^{Z_g}$.

Cooling effect constraints (for all $1 \le k \le K$)

$$\begin{aligned} 10/11 e_k + 10/11 r_k + \sum_{g,p} x_{g,p,k} &= J_k \\ 3e_k &= r_k \end{aligned}$$

The first equation ensures that the right amount of cooling material is used. The second one leads to the desired iron ore / additional hot metal proportion (remember that for one unit of iron ore, there must be three units of additional hot metal).

Material constraints (for all $1 \le k \le K$)

$$A_{\mathrm{Cr}}\left(e_k\mathrm{Cr}_E + (R_k + r_k)\mathrm{Cr}_R + \sum_{g,p}(x_{g,p,k}\mathrm{Cr}_{\mathfrak{K}_{\mathfrak{g},\mathfrak{p}}})\right) \le \overline{\mathrm{Cr}}_k\left(e_k + R_k + r_k + \sum_{g,p} x_{g,p,k}\right)$$

$$e_k\mathrm{Fe}_E + (R_k + r_k)\mathrm{Fe}_R + \sum_{g,p}(x_{g,p,k}\mathrm{Fe}_{\mathfrak{K}_{\mathfrak{g},\mathfrak{p}}}) \ge \underline{\mathrm{Fe}}_k\left(e_k + R_k + r_k + \sum_{g,p} x_{g,p,k}\right)$$

$$e_k \le 9$$

$$\sum_{\mathfrak{K}_{\mathfrak{g},\mathfrak{p}}=\mathfrak{k}} x_{g,p,k} \le \overline{N}_\mathfrak{k} \quad \text{for all classes } \mathfrak{k} \in \mathfrak{K}$$

The first set of inequalities gives the maximum relative tramp element amount, the second set the minimum relative iron amount. The last ones take care that from iron ore and from every scrap class, only the specific maximum absolute amount is used.

Transportation constraints

$$\sum_{g,p} w_{g,p} \le 8$$

$$\sum_{g} s_g \le 3$$

$$w_{g,p} \le w_{g,p-1} \quad \text{for single-class tracks } g$$

As we have described earlier, a train can have up to eight cars which must come from no more than three different tracks. On single-class tracks, cars can only be taken from the front (so that if you wish to take the second car on the track, you must also order the first one).

We now need to link the binary variables for cars and tracks with the continuous variables for the respective scrap amounts. This is done in the following way and explained below (see [8]):

$$\sum_{k=1}^{K} x_{g,p,k} \le w_{g,p}M_{g,p} \qquad \text{all } (g,p)$$

$$\sum_{k=1}^{K}\sum_{p=1}^{Z_g} x_{g,p,k} \le s_g \cdot \left(\sum_{p=1}^{Z_g} M_{g,p}\right) \quad \text{all } g$$

The reader may take a look at the first set of inequalities. If a car is chosen for the train (i.e. $w_{g,p} = 1$), then up to $M_{g,p}$ units of scrap can be taken from this car. On the other hand, if $w_{g,p} = 0$, we have $\sum_{g,p,k} x_{g,p,k} = 0$ and finally $x_{g,p,k} = 0$ for $1 \leq k \leq K$.

Objective function

Our objective function is the cost function for the demanded scrap, iron ore and additional hot iron. It can be expressed as follows:

$$\left(\sum_{k=1}^{K} e_k P_E + r_k P_R\right) + \left(\sum_{g,p} w_{g,p} M_{g,p} P_{\mathfrak{K}_{g,p}}\right)$$

The first sum gives the iron ore and additional hot metal costs, the second one the costs of scrap in the chosen cars. Note that even if only a part of the scrap of a car is used, the whole car has to be paid for.

4 Solving the MIPs

The MIPs resulting from the discussed model have been solved with the commercial LP/MIP solver CPLEX (version 4.0.7 for HP-9000/735-125 workstations) [1], representing an efficient implementation of the linear programming based branch-and-bound algorithm [8]. In particular, CPLEX has been successfully used for solving problems arising from academic as well as from real-life applications. Furthermore, this solver is available on a broad variety of computer systems (including MS-DOS and many UNIX systems).

CPLEX accepts data in standard formats like MPS-files. We implemented perl scripts which convert the HKM steelworks data into a CPLEX readable file (perl is a "script language" like awk or sed, it is usually known from UNIX systems, but also available for MS-DOS).

We have also implemented a CPLEX/LEDA (LEDA is a C++ library providing common complex data types and graph drawing routines, [7]) based graphic output solution software called OSCAR. A screenshot is shown in Fig. 5. On the top window, a train and the scrap mixture for the next series is shown. The bottom window gives the scrap yard track status: The highlighted cars are suggested for the next train. Multi-class tracks are marked with the keyword "SAMMEL" (for the German word "Sammelgleis").

5 Accelerating the MIP solution process

Progress in computer technology and in design of efficient algorithms and their implementation together with mathematical advance lead in some cases to satisfactory MIP solution times. Unfortunately the MIP of the pure problem formulation described above can not be solved in the desired time of 20 seconds. We briefly present some model improvements, which lead to sufficient solution times. These techniques are primarily based on techniques of *polyhedral optimization*. We improve the relaxation of the MIP by *valid inequalities* or *cuts* and do some preprocessing which results

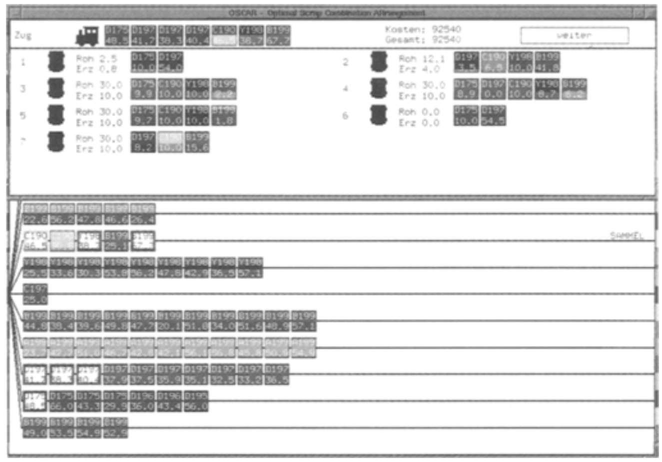

Fig. 5. Screenshot of the optimization software OSCAR

in coefficient reduction and fixing or elimination of variables (cf. [4]). In the last decade, these techniques which provide a *closer* linear description of the polytope associated with the MIP, were applied to programs with combinatorial structure [3]. The success of these methods additionally are due to improvements of the simplex algorithm and interior point methods for solving *linear programs* (LP). For an investigation of preprocessing techniques, we refer to [9].

Variable fixing and eliminating

To reduce the size of MIPs, it is often helpful to take a closer look at the problem structure. Sometimes, there are variables whose values in an optimal solution can be easily determined in advance. Thus, they can be replaced by constant values. This process is called *variable fixing*.

Consider a single-class track with a scrap class $\mathfrak{k}$ with a small value of $\overline{N}_{\mathfrak{k}}$ (i.e. only few tons of this scrap can be used in a process). If the first n cars on the track contain $K \cdot \overline{N}_{\mathfrak{k}}$ or more tons of scrap, cars behind these are never needed (which leads to $w_{g,n+1} = \ldots = w_{g,Z_g} = 0$).

A similar strategy can be applied for single-class tracks containing an expensive scrap class which obeys all material restrictions. Furthermore variables $w_{p,g}$ with $p > 8$ for single-class tracks can be fixed to 0, because of the limited number of cars in the train.

Another variable eliminating possibility results from the combinatorial structure of the problem: On single-class tracks, taking the first car into the train is equivalent to taking the track itself for the train. Thus $w_{g,1} = s_g$ for single-class tracks, so we can delete one of the variables.

Coefficient reduction

In an LP-relaxation-based branch-and-bound process, every LP solution with non-integer values for the integer variables leads to the generation of subproblems (the branch-and-bound tree).

Often coefficients in the constraint matrix can be modified (without changing the optimal MIP solution) so that already the LP solution becomes integer in some components. Let us focus on the following example: A multi-class track contains twelve cars, each holding 50 t of scrap (that is 600 t altogether). We then have the inequality

$$\sum_{p} \sum_{k=1}^{K} x_{g,p,k} \leq 600 s_g.$$

Since only eight cars can be selected, the sum never exceeds 400, and the constraint can be replaced by

$$\sum_{p} \sum_{k=1}^{K} x_{g,p,k} \leq 400 s_g,$$

which is still correct for all solutions with an integer value for s_g, but makes some non-integer solutions infeasible.

In order to use this technique on our model, we need better bounds for the scrap sums. These can be found by considering that

- only scrap from eight cars can be taken,
- some scrap combinations are not allowed because of their tramp elements (this is in particular useful for tracks containing the cheap scrap with high relative tramp element amounts).

Cutting planes

Sometimes, non-integer solutions can be eliminated by adding constraints (which are not violated by any integer solution) arising from the combinatorial structure of the problem. Such constraints are called *cutting planes* (see [8] for an introduction, a survey written in German can be found in [5]).

We give an example for cutting planes in the scrap optimization model: ¿From the fifth cars of all single-class tracks, only one can be taken into a train (otherwise, there would be more than eight cars). Still, there is the non-integer solution of taking $8/15$ of each of the first five cars on three single-class tracks. The non-integer solution can be excluded by adding

$$\sum_{g \in G'} w_{g,5} \leq 1,$$

where G' denotes the set of single-class tracks. A similar cutting plane can be found for the third cars on single-class tracks.

We add a couple of useful cutting planes to our model. A detailed description can be found in [6].

Priority orders

One of the most efficient methods for improving solution performance besides polyhedral improvements is to assign a *branching priority* for variables (see [1]). Variables with higher priorities will be selected and branched upon in the branch-and-bound tree before variables with lower priorities. We put high priorities on the variables $w_{g,1}$ which indicate if the train includes some cars of the track g. The priority orders implemented in the CPLEX package also permit the specification of branching direction (up: variable fixed to 1, down: variable fixed to 0). For the variables mentioned above we figured out that branching down first yields much better solution performances.

6 Computational results

HKM have supplied us with several production test files. Table 1 shows relevant data on the solution process for 17 representative real-life instances. The columns contain the following data: number of constraints, variables, and nonzeroes, LP relaxation value, MIP optimal value, and MIP solution time.

Table 1. Model data for the HKM instances

Without accelerating techniques						
Test	#C.	#V.	#≠0	LP Sol.	MIP Sol.	Time
1	229	481	4074	111258	111707	0.84 s
2	310	725	6300	69412	69969	137.14 s
3	306	746	6017	97415	97500	42.98 s
4	308	715	5914	94675	94980	16.97 s
5	343	741	6781	76667	77801	1.28 s
6	319	677	6284	92648	94790	26.54 s
7	342	758	6925	91805	92844	1.22 s
8	318	685	6696	96508	97612	6.85 s
9	343	782	6215	99781	100578	8.63 s
10	393	911	7210	92962	93778	12.47 s
11	310	731	6346	92173	92977	6.81 s
12	343	742	6331	88265	88863	1.28 s
13	343	742	6606	98912	99433	8.33 s
14	418	959	9206	90723	92597	20.77 s
15	389	982	8068	97886	98340	2.20 s
16	322	796	6518	98806	99336	973.10 s
17	534	1299	10880	71510	75280	12468.31 s

With accelerating techniques						
Test	#C.	#V.	#≠0	LP Sol.	MIP Sol.	Time
1	262	440	3782	111258	111707	0.91 s
2	377	640	5687	69755	69969	10.00 s
3	323	624	5013	97415	97500	18.94 s
4	316	592	4879	94675	94980	3.56 s
5	389	624	5785	76667	77801	2.39 s
6	335	568	5289	92749	94790	5.25 s
7	364	648	5927	91830	92844	1.12 s
8	414	664	6670	96576	97612	3.31 s
9	417	751	6079	99781	100578	4.41 s
10	437	824	6568	92962	93778	7.12 s
11	406	720	6389	92448	92977	5.49 s
12	432	729	6351	88614	88863	1.68 s
13	427	712	6482	99025	99433	6.21 s
14	472	880	7809	91358	92597	8.87 s
15	475	944	7889	98139	98340	1.01 s
16	403	784	6524	99335	99336	16.28 s
17	689	1280	10937	71954	75280	11.30 s

As one can see, the use of MIP acceleration techniques is essential for a fast calculation as requested by HKM (remember the demanded time limit of 20 s) and yield a speedup of factor 1000 for instance number 17.

Table 2 shows a cost comparison of the HKM heuristic (column "HKM") and our MIP model ("MIP") for the instances. The solutions generated from our model promise scrap combinations of significiantly reduced cost than those

Table 2. Cost comparison

Solution costs					
Test	HKM	MIP	Test	HKM	MIP
1	115700	111707	10	99142	93778
2	76398	69969	11	100292	92977
3	99902	97500	12	97055	88863
4	99267	94980	13	100190	99433
5	86510	77801	14	94258	92597
6	98100	94790	15	103088	98340
7	95312	92844	16	101957	99336
8	102909	97612	17	81054	75280
9	106698	100578			

from the present HKM heuristic discussed earlier. The figures in Table 2 do not represent a particular monetary unit but point at the relative cost savings from 0.8% to 10.1% with an average improvement of approximately 5%.

7 Limitations and extensions

As stated in the model introduction, we have done some simplifications on the real-world situation. The most obvious one is the calculation of a single train only. If all necessary data is available for an enlarged time horizon, the simultaneous computation may yield another cost reduction.

Multi train models

The easiest way of simultaneous treatment of t trains is obtained by fixing the number of processes for each train. In this case, one can easily add another index for the train number to the x-, w- and s-variables. Additional constraints are needed: For example, a car can only be integrated into one train.

It is even more desirable to let the model determine an assignment for processes to trains. This can also be handled by using more variables (see [6]).

The great advantage of a multi train model is the consideration of the global planning situation. The single train model is "greedy": It will always search for the cheapest solution for one train without regarding that a slighty more expensive solution will lead to a large cost saving for the next train.

One main reason (besides increased solution times) for disregarding multi train models in practice is the highly unpredictable planning situation in the steelworks. Because of the complex structure of steel production, there are often disturbances which lead to massive changes in the production schedule and completely destroy the quality of a solution corresponding to a long planning period.

The "single train" model presented in this paper obeys the on-line characteristic of the present situtation, because the dispatcher can initiate the computation just before ordering a train from the scrap yard. Changes in the production schedule afterwards cannot be taken into account by manual orders either.

Additional features

Some additional features can easily be added to the MIP model. Different cooling effects can be taken into account by introducing particular coefficients in the cooling effect constraints. Transport costs for using cars and tracks can also be considered. Other linear constraints such as scrap volume can be taken into account.

Another idea is the extension of the optimization to other problems related to the scrap problem. This may involve the movements of cranes that take the scrap from the cars to the transport containers [2] or even the action of assembling the train itself on the scrap yard.

Using the model for simulations

Moreover, the MIP model will be useful as a simulation tool. Simply by changing coefficients one may examine the effects of small changes in prices, scrap classes, tramp element restrictions, ...

Another idea is to change the restrictions for the maximum track number. It is possible that essentially better solutions are generated if four or more tracks can be used for one train, even at higher transport costs.

8 From theory to practice

HKM intend the developed software to be installed in their own computer system. The main part of the present HKM scrap information system runs on a process computer under an operating system called MAX32. For reasons of availability of the CPLEX solver, our software OSCAR will be implemented on a separate UNIX system. The process computer must send the data of the scrap yard and of the processes to the UNIX machine, which, in turn, provides the optimization results for further use in the scrap information system on the process computer. Since the size of the data is quite small no loss of performance is expected with respect to communication delays between the two machines.

It is worth mentioning that not only technical and implementational issues are of interest when regarding the personnel's *acceptance* of new technologies. As we know from experience, "black box" methods, such as the use of a mixed integer program, are likely to be disregarded when they are not properly introduced to the operating personnel. Nonobvious changes in the structure of solutions have to be carefully explained and made comprehensible. It is even more important to see that a mathematician's *idealistic* view of the world has to be complemented with practitioner's experience. In every day operation, data often are just an estimate and consequently not always that complete and consistent as we assumed in this paper. By establishing a certain *error tolerance* one has to ensure that our program *always* delivers a solution even if mathematically no feasible one exists. Closely related is the fact that small changes in the input data may often lead to completely different, and thus unstable and confusing solutions. Consequently, the conflict between optimality and robustness of solutions should rather be decided in favour of reliability, and implemented in the system accordingly. Besides that, the computer results have to be regarded as a *proposal* only, so that the planner may resort to alternative dispatching at any time. This is not only important for psychological reasons, but also imperative in situations that require immediate or exceptional decisions, as they sometimes arise in a real time setting. Moreover, it is advisable to maintain some degree of freedom in the choice of certain parameters, in our case the maximal number of cars per train, prices for scrap, or relative amounts of tramp elements, just to mention a few. This flexibility, often referred to as "what-if analysis", enables dispatchers as well as HKM's management to simulate altered operations, thus possibly identifying further economization potential.

Clearly, the implementation of reliability and stability will reduce the savings of about five per cent, calculated for our *pure* model. Nevertheless, the mathematical optimization methods will lead to *remarkable* savings with feasible solutions, an aspect which is ignored by the current strategy.

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