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**A scheduling system for the steelmaking □ continuous casting process □
A case study from the steel-making industry**

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A scheduling system for the steelmaking – continuous casting process – a case study from the steel-making industry

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This paper describes the models, algorithms and implementation results of a computerized scheduling system for the steelmaking – continuous casting process of a steel plant in Austria. The basis for the scheduling task is a preliminary production schedule for the continuous casters (sequence of charges that must be consecutively cast and their allocation to the continuous casters). The scheduling task can be structured as four subproblems: (1) Scheduling the continuous casters. (2) Allocation of the charges to the parallel facilities at the upstream stages (converter and refining facilities). (3) Sequencing the charges at the converters and refining facilities. (4) Exact timing of all operations. The heuristic algorithm consists of three planning levels: (1) Scheduling the continuous casters, considering the capacity restrictions at the upstream stages and the limited availability of hot metal. (2) Scheduling of the converter and refining facilities according to priorities, performing allocation and sequencing. (3) Improving the schedule by means of an LP model. The system visualizes the schedules as Gantt

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3 charts. Extensive numerical tests with real-life data and more than two years of
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5 experience with the implementation demonstrate that the system produces
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7 reasonable schedules and is accepted by the planners.
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12 *Keywords:* Steel industry; Production planning; Scheduling
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For Peer Review Only

1 Introduction

Iron and steel production is one of the major industries in the world economy, providing raw materials for a number of important industries. The manufacturing process that transforms iron ore, scrap and some other input factors into steel products such as plates and tubes is a multi-stage process that can roughly be divided into three phases.

(1) Ironmaking: production of molten iron (termed hot metal) mainly from iron ore, coke and a fluxing agent.

(2) Steelmaking - continuous casting: Processing of the hot metal to steel with a well-defined chemical composition and solidifying the steel to cuboids, called slabs.

(3) Production of finished products by hot rolling, cold rolling, hot-dip galvanizing, etc.

In this paper we consider the steelmaking - continuous casting phase (abbreviated SM-CC), which is often, as in our case, a bottleneck in the manufacturing process (see Tang et al. 2002, p. 55). Furthermore, due to a number of technological constraints described below, the start and finish dates of the operations should be predictable and the consequences of disruptions such as machine breakdowns should be known as soon as possible.

These objectives – throughput maximization due to the bottleneck situation and predictability of the schedule – make scheduling of the SM-CC process an extremely important task that is very difficult due to the complex technology of the process. This was the motivation for a large steel plant in Austria to develop and implement a computerized scheduling system – similar to a “Leitstand” (Pinedo 1995, p. 304ff.) – for performing this scheduling task. This paper describes the scheduling problem and an approximate mathematical model of this problem, presents a three-stage heuristic solution procedure, and reports on the implementation results.

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3 The paper is organized as follows: Section 2 describes the SM-CC process under
4 consideration. Section 3 describes the scheduling problem and the interface to the upper
5 planning level. Section 4 provides an overview of the related literature. Section 5 presents an
6 MILP model for the scheduling problem. In section 6 the heuristic three-stage solution
7 procedure is presented. Section 7 describes the course of the project and the implementation
8 results. Some conclusions are given in section 8.
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21 **2 The steelmaking – continuous casting process under consideration**

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24 The SM-CC process (figure 1) consists of four phases: Hot metal preparation,
25 steelmaking (LD process), refining (secondary metallurgy) and continuous casting.
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Figure 1: The steelmaking – continuous casting process under consideration

The hot metal (from the blast furnace) is poured into a *transfer ladle* and enters the hot metal preparation where it is deslagged and desulfurized. After this operation the hot metal can be conveyed directly to the converter or stored in a *hot metal mixer*, which serves as a buffer. After pouring the hot metal into the converter or the hot metal mixer the transfer ladle is idle and can be used again (first ladle loop: loop of the transfer ladles). The average production rate of hot metal over time is constant over the planning horizon; the variations in the production rate are random.

After the converter is filled with scrap and hot metal (in this sequence) the LD-process starts for this *charge* of steel (about 160 tons). After finishing the LD-process the converter is *tapped*, that is, the *crude steel* is poured into a *ladle*, which is required at this time. *Refining*, which transforms the crude steel into the *steel grade* required for the customer order, is performed by one *conditioning stand*, two *ladle furnaces* and two *vacuum degassing units*. Refining can require alloying, desulphurization, dephosphorization, degassing, etc.

The *continuous casters* (abbreviated CC; one double-strand and three single-strand) solidify the steel to slabs (typically 215 x 1650 mm, up to 31 tons) in a continuous process. The steel is poured from the ladle into a *tundish* and solidifies in a *crystallizer*. The steel is moved downward at 1.00 – 1.80 m/min and is cooled until it can be cut to the appropriate length. If the casting process is interrupted, a restart lasts about one hour (setup time).

After the continuous casting process is finished, the ladle must be reworked at the *tilting device* before it is available for the next charge (second ladle loop). All transport operations are performed by cranes. Four cranes are available for each ladle loop.

The production volume is about 100 charges per day, about 4.4 million tons of crude steel per year. The slabs are processed by two rolling mills (hot rolling mill and plate rolling

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3 mill), either directly with short delay (hot charging in order to save energy) or after storing the
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6 slabs in a slab yard and reheating (see Tang et al. 2001 for alternative ways to integrate
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8 continuous casting and rolling mills).
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10 For most charges the facilities that have to perform the operations are not fixed; the
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12 allocation of charges to facilities working in parallel is a part of the scheduling problem.
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14 Furthermore, the number of operations need not be fixed. For instance, for some charges the
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16 refining operation can be performed by the ladle furnace or by the degassing units, but it
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18 might also be possible to split the operation between a ladle furnace and a degassing unit.
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20 Usually there are preferences for this allocation due to production technology or
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22 transportation, so there are standard routes and alternative routes. These (soft) routing
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24 constraints are modelled as alternative routes and route preferences for each steel grade
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26 (figure 2).
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Figure 2: Route preferences for a steel grade (example)

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52 The definition of the route preferences is backward: If the charge is processed by a
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54 certain (successor) facility, then the priorities of the predecessor facilities are as specified. No
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56 information on subsequent stages is used, that is, the stage after the successor facility under
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58 consideration is not relevant.
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The following additional properties of the manufacturing process are assumptions in the subsequent model:

- The processing times of all charges at all facilities and the transportation times at the cranes are known and sequence-independent.

- The throughput element (sequence of actions when an operation is performed), as seen by the facility, the charge and the crane, is depicted in figure 3.
- The transports are modelled as operations, the cranes are modelled as facilities. The positioning time of the crane is the pre-operation time of the transport operation.

Figure 3: Throughput element of an operation

Lower and upper bounds on the waiting times can be specified. The time the facility is occupied before and after the operation (pre- and post-operation time) and the positioning time of the cranes are fixed.

Planned downtimes at the facilities have to be considered in the schedules. The production technology can require three types of planned downtimes: Downtimes with fixed start date and duration; downtime after processing a specific operation (this can be modelled as a post-operation time; see figure 3); downtime after a certain number of charges at a certain facility.

3 Description of the SM-CC scheduling problem

In order to describe the scheduling problem under consideration and the subsequent modelling decisions, we have to define the interface between the SM-CC scheduling problem and the upper planning level that set the targets for SM-CC scheduling. A description of the planning system for the entire steel plant is beyond the scope of the paper, so we limit our scope to the planning system that immediately sets the targets for SM-CC.

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3 We define a *cast* as a sequence of charges that have to be cast consecutively on the
4 same continuous caster. A cast consists of one or (usually) several *virtual tundishes*, defined
5 as the sequence of charges that are consecutively cast using the same tundish. If the tundish
6 has to be changed (due to its limited endurance or to sequencing constraints), the tundish
7 change can be performed in about five minutes without interrupting the casting process. After
8 finishing a cast, the continuous caster is stopped and remains idle for at least one hour; then
9 the next cast can be started.

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11 The planning level that sets the targets for SM-CC-scheduling is an integrated
12 scheduling of continuous casters and rolling mills. This planning level determines the
13 following:

- 14 (1) the casts, that is, the charges, their sequence within the cast and the planned
15 cast breaks (usually after a virtual tundish);
- 16 (2) the allocation of the casts to the continuous casters;
- 17 (3) the sequence of casts on the continuous casters (which can be changed
18 manually by the dispatchers at the continuous casters);
- 19 (4) the (preliminary) start and finish dates of the casts at the continuous casters.

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21 This planning level considers (1) the demand of the rolling mills, including hot
22 charging, (2) sequencing constraints at the continuous casters, (3) rules that account for
23 limited availability of upstream facilities and hot metal. For instance, if a degassing unit is
24 down for several hours, the planning system will avoid scheduling many charges that require
25 the degassing units.

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27 The start and finish dates of the casting operations that are set by this integrated
28 planning often do not allow a feasible schedule because finite capacities at the upstream
29 facilities are not considered in sufficient detail. Thus SM-CC scheduling takes the casts and
30 their allocation to continuous casters from this upper planning level. Furthermore, SM-CC
31 scheduling derives rules for the relative positioning of the casting dates on different

continuous casters (termed *cast topology*) from the preliminary timing. This cast topology can determine that, e.g., a cast on CC5 can start after a certain cast on CC 4 is finished. It binds SM-CC scheduling to certain rules for the allocation of scarce hot metal or capacity.

SM-CC scheduling has to schedule all casts and all charges on the facilities, cranes and ladles. This decision problem can be structured into four subproblems as follows:

- *Scheduling the continuous casters*: Determining the casting speed and the start and finish dates of each cast (and each charge within the cast).
- *Allocation* of charges to the facilities working in parallel.
- *Sequencing* of the charges on each facility.
- *Timing*: Determining the start and finish dates of each operation (each charge on each facility).

The main objective is to maximize the output (number of charges per day). Since the scheduling problem is static (no arrival of new orders during the planning horizon), minimizing the makespan is an equivalent objective. However, some other criteria have to be considered as well (see section 5.2). The length of the planning horizon is typically 72 hours, so about 300 charges are to be scheduled.

4 Related literature

Production planning and scheduling in the steel industry has been the topic of extensive research efforts (for an overview, see Tang et al. 2001), but the SM-CC scheduling problem as defined in our case has received limited attention in the literature. When we exclude hot metal preparation, cranes and the continuous casters (where allocation and sequencing is already performed), the manufacturing system under consideration can be modelled as a three-stage hybrid flow shop with possible skipping of one (refining) stage and dual resource constraints (facilities and ladles). The two-stage hybrid flow shop scheduling

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3 problem is NP-complete (Gupta 1988), so we can expect that no efficient algorithm for a
4 mixed-integer programming model of the SM-CC scheduling problem (see section 5) exists.
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7 For small problems, models for scheduling steelmaking-continuous casting can be solved to
8 optimality by standard software (Bellabdaoui and Teghem 2006), but for our problem with up
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11 to 300 charges (if the entire horizon of 72 hours is considered) this seems unrealistic.
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15 Several approaches have been pursued in the literature to perform SM-CC scheduling,
16 mainly based on operations research, artificial intelligence and human-computer interaction
17 (similar classification in Tang et al. 2001). For our purpose, mainly operations research
18 models and rule-based approaches are relevant for schedule generation. We do not
19 specifically focus on human-computer interaction for schedule manipulation (see Pinedo
20 1995, p. 288), although this is an important topic also in our case.
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29 Practical SM-CC scheduling problems with *one* continuous caster can be solved
30 within 1-3% from optimality using decomposition techniques (creating schedules for each
31 cast separately and then concatenating the schedules; see Harjunoski and Grossmann 2001;
32 the planning system presented there is more comprehensive and also encompasses other
33 subproblems) or by partial enumeration techniques in a plant that is a flow shop where the
34 allocation problem is not relevant (see Pacciarelli and Pranzo 2004). A generalization of these
35 approaches to two or more continuous casters, adding the problem of the relative positioning
36 of the casts over time, is not obvious. Tang et al. (2000) and Harjunoski and Grossmann
37 (2001) describe LP models that determine the start and finish dates and the casting speeds of
38 all charges, assuming that all allocations and sequences are fixed. This solves only a small
39 subproblem of SM-CC scheduling, but we use this idea in our hierarchical system.
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54 Tang et al (2002) formulate the SM-CC scheduling with several continuous casters as
55 a mixed-integer programming model and develop a solution method based on Lagrangean
56 relaxation. Two groups of coupling constraints are relaxed: The precedence constraints on the
57 continuous casters and the machine capacity constraints. The resulting subproblems for each
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3 charge are solved by dynamic programming, a feasible solution to the original problem is
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5 obtained by a heuristic. Huegler and Vasko (2007) develop a heuristic that calculates an
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7 SM-CC schedule for pre-determined casting times and start dates of the charges on the
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9 continuous caster. An evolutionary programming algorithm is used to optimize the casting
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11 times. Bellabdaoui et al. (2005) develop a construction heuristic that first schedules the
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13 continuous casting and refining stage and then the converters. If necessary, the casting
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15 operations can be slowed (which is the only possibility for casts that already have been
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17 started) or delayed if necessary. In these papers no practical implementation has been
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19 reported.
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25 Knowledge-based systems have been developed both for schedule generation and
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27 rescheduling. For an overview, see Tang et al. (2001); for the development of a knowledge
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29 model for managing schedule disturbances, see Roy et al. (2004). Human dispatchers utilize
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31 extensive knowledge usually acquired in many years of experience, which often is
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33 indispensable for real-life scheduling (see MacKay and Wiers 2006 for the “human factor in
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35 planning and scheduling”). This indicates that algorithms for schedule generation and
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37 modification must be integrated carefully into the scheduling process and linked with the
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39 expert knowledge of the dispatchers.
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44 We can conclude that only a small number of OR algorithms have been developed to
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46 optimize the SM-CC process and that the very complex situation in the plant under
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48 consideration is not covered by these methods. Only the subproblem of timing and optimizing
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50 the casting speeds can be solved by standard techniques. A rule-based approach can be
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52 beneficial for integrating the expert knowledge of the dispatchers into the automatic schedule
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54 generation and into the rescheduling activities.
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58 In the following a new algorithm for solving the SM-CC problem is developed that
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60 combines these techniques in order to generate schedules. Managing schedule disturbances is
left to the problem-solving ability of the human dispatchers.

5 The MILP model for SM-CC scheduling

The SM-CC scheduling problem can be formulated as a mixed-integer model; models of this type are given in Tang et al. (2002), Bellabdaoui and Teghem (2006). In the following a model formulation is given that considers some additional issues that are important in our case: Explicit modelling of the ladle loop, alternative routes with the number of operations depending on the route, and limited hot metal supply. The model also clarifies that under moderate assumptions it is an MILP model.

For the mixed-integer programming formulation the material flow is modelled as follows:

We consider a static scheduling model with J charges ($j=1, \dots, J$) that have to be processed. For converter and refining operations each charge j is represented by a set of virtual charges $\hat{j} \in C_j$ that represent the alternative routes from which exactly one route has to be selected. The preferences are modelled as penalties in the objective function. Each virtual charge \hat{j} consists of $N_{\hat{j}}$ operations $n=1, \dots, N_{\hat{j}}$ with fixed sequence. Each operation n can be performed by a subset $F_{n, \hat{j}}$ of the facilities. This is especially relevant for transportation, which frequently can be allocated arbitrarily to the cranes, but it can also reduce the number of virtual charges. (\hat{j}, n) denotes operation n on virtual charge \hat{j} .

Each charge requires a ladle from the time the converter is tapped. The charge is allocated to the ladle until the ladle is transported from the tilting device to the converter; then the next charge can be allocated to the ladle. $n = N_{\hat{j}}$ denotes the transport of the ladle from tilting device to converter.

The cumulative hot metal supply over time is known and the cumulative hot metal requirements must not exceed the cumulative supply. The material flow to and from the hot

metal mixer is not included in the model and has to be determined at the subsequent execution level. The model also does not consider the limited availability of transfer ladles.

5.1 Symbols

Indices and sets

j, k (or \hat{j}, \hat{k})	Charges (or virtual charges)
m	Facilities (including cranes)
p	Ladles
$n=0, 1, \dots, N_j$	Operations on a charge j . $n=0$ denotes transport of the scrap to the converter. $n=1$ to N_j denote the sequence from deslagging, transportation, converter, ...; N_j is the transport of the ladle from the tilting device to the converter for the next charge.
F_{nj}	Set of the facilities that can perform operation n on charge j
C_j	Set of virtual charges that represent the alternative routes of charge j
 <i>Parameters</i>	
A_{jnm}	Operation time of operation n of charge j on facility m
$A_j^{CC(\min)}, A_j^{CC(\max)}$	Minimum and maximum casting time of charge j on the CC

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P_{jnm} Post-operation time of operation n of charge j after processing on facility m (facility occupied)

R_{jnm} Pre-operation time of operation n of charge j before processing on facility m (facility occupied). If facility m is a crane, R_{jnm} denotes the positioning time.

Z Very large number (exceeding the length of the planning horizon)

B_j, U_j Setup time and time for tundish change before charge j on the continuous caster

$V(j, CC)$ Index of the predecessor of charge j on the continuous caster

H_j Amount of hot metal for charge j

$E(t)$ Cumulative hot metal supply at time t

D_j Target due date for charge j

Variables

Binary variables

$$\xi_j = \begin{cases} 1 & \text{if virtual charge } \hat{j} \text{ is selected} \\ 0 & \text{otherwise} \end{cases}$$

$$\delta_{jn,ko,m} = \begin{cases} 1 & \text{if operation } n \text{ of charge } j \text{ is processed before operation } o \text{ of charge } k \text{ on facility } m \\ 0 & \text{otherwise} \end{cases}$$

$$\hat{\delta}_{jkp} = \begin{cases} 1 & \text{if charge } j \text{ is sequenced before charge } k \text{ on ladle } p \\ 0 & \text{otherwise} \end{cases}$$

$$\delta_{jk}^s = \begin{cases} 1 & \text{if charge } j \text{ is started (deslagging) before charge } k \\ 0 & \text{otherwise} \end{cases}$$

$$\phi_{jnm} = \begin{cases} 1 & \text{if operation } n \text{ of charge } j \text{ is allocated to facility } m \\ 0 & \text{otherwise} \end{cases}$$

$$\hat{\phi}_{jp} = \begin{cases} 1 & \text{if charge } j \text{ is allocated to ladle } p \\ 0 & \text{otherwise} \end{cases}$$

$$\beta_j = \begin{cases} 1 & \text{if a cast break occurs before charge } j \\ 0 & \text{otherwise} \end{cases}$$

Continuous variables

a_j^{cc} Casting time of charge j on CC

\tilde{a}_j^{cc} Relative casting time of charge j on CC, standardized to the interval $[0; 1]$

b_j^{add} Duration of cast break before charge j on CC that exceeds the setup time (the total idle time on the CC before charge j is $b_j^{add} + B_j$)

d_j^{cc-}, d_j^{cc+} Negative and positive deviation of the relative casting time of charge j from 5-charge average

f_j^+, f_j^- Positive and negative due date deviations of charge j

w_{jn}	Waiting time of operation n of charge j
x_{jn}	Start date of operation n of charge j
x_j^{CC}	Start date of charge j at the continuous caster

All continuous variables are non-negative.

5.2 Model formulation

5.2.1 Constraints

Casting sequence and cast breaks for charges without tundish change

$$\begin{aligned} x_{V(j,CC)}^{CC} + a_{V(j,CC)}^{CC} + B_j \beta_j + b_j^{add} &= x_j^{CC} \\ Z \beta_j &\geq b_j^{add} \end{aligned} \quad \text{for all } j \quad (1)$$

The cast break time $B_j \beta_j + b_j^{add}$ is the difference between start date of charge j and finish date of its predecessor. If a cast break occurs, the setup variable β_j must be 1, hence the minimum duration of the cast break is the setup time B_j .

Casting sequence and cast breaks for charges with tundish change

$$x_{V(j,CC)}^{CC} + a_{V(j,CC)}^{CC} + B_j \beta_j + b_j^{add} + U_j (1 - \beta_j) = x_j^{CC} \quad \text{for all } j \quad (2)$$

This is the same as equation (1), but considers the fixed time for tundish change if no cast break occurs. In the case of a cast break a setup is necessary, this includes the time for tundish change.

Casting sequence and cast breaks for charges with setup time (cast break implied)

$$x_{V(j,CC)}^{CC} + a_{V(j,CC)}^{CC} + B_j \leq x_j^{CC} \quad \text{for all } j \quad (3)$$

If a setup time between charges $V(j,CC)$ and j is necessary, the casting process can be resumed at an arbitrary time after finishing the setup. The constraint can be obtained from equation (1) by setting $\beta_j = 1$.

Range of feasible casting speed

$$A_j^{CC(\min)} \leq a_j^{CC} \leq A_j^{CC(\max)} \quad \text{for all } j \quad (4)$$

The casting times can be varied by varying the casting speed, but must fall within upper and lower limits for technological reasons.

Change of casting speed

Definition of the relative casting time, standardized from 0 (minimum time) and 1 (maximum time)

$$\tilde{a}_j^{CC} = \frac{a_j^{CC} - A_j^{CC(\min)}}{(A_j^{CC(\max)} - A_j^{CC(\min)})} \quad \text{for all } j \quad (5)$$

Then the positive and negative deviations of the relative casting time are calculated as the deviations from the average of a 5-charges window:

$$\frac{1}{5} \left(\sum_{i=1}^2 \tilde{a}_{V(i,j)}^{CC} + \tilde{a}_j^{CC} + \sum_{i=1}^2 \tilde{a}_{N(i,j)}^{CC} \right) = \tilde{a}_j^{CC} + d_j^{CC-} - d_j^{CC+} \quad \text{for all } j \quad (6)$$

$\tilde{a}_{V(i,j)}^{CC}$ ($\tilde{a}_{N(i,j)}^{CC}$) is the i -th predecessor (successor) of charge j on the continuous caster.

The deviations d_j^{CC-} and d_j^{CC+} are included into the objective function.

Due date deviations of the charges

$$f_j^+ - f_j^- = x_j^{CC} + a_j^{CC} - D_j \quad \text{for all } j \quad (7)$$

These equations, together with the non-negativity and the positive cost coefficients of f_j^+ and f_j^- in the objective function, set the positive and negative due date deviations f_j^+ and f_j^- to the positive or negative difference between target due date D_j and actual due date $(x_j^{CC} + a_j^{CC})$.

Selection of virtual charges

$$\sum_{j \in C_j} \xi_j = 1 \quad \text{for all } j \quad (8)$$

For each charge j exactly one route (virtual charge \hat{j}) must be selected.

Start dates of operations on the facilities (production sequence as seen by the facility)

$$x_{\hat{k}n} + A_{\hat{k}nm} + P_{\hat{k}nm} + R_{\hat{j}om} \leq x_{\hat{j}o} + Z(3 - \phi_{\hat{k}nm} - \phi_{\hat{j}om} - \delta_{\hat{k}njom})$$

$$\forall \hat{j}; \forall \hat{k} \neq \hat{j}; \forall n = 0, \dots, N_{\hat{k}} \neq n_{\hat{k},CC}; \forall o = 1, \dots, N_{\hat{j}} \neq n_{\hat{j},CC}; \forall m \in F_{n\hat{k}} \cap F_{o\hat{j}} \quad (9)$$

$$x_{\hat{j}o} + A_{\hat{j}om} + P_{\hat{j}om} + R_{\hat{k}nm} \leq x_{\hat{k}n} + Z(3 - \phi_{\hat{j}om} - \phi_{\hat{k}nm} - \delta_{\hat{j}o\hat{k}nm})$$

$$\forall \hat{j}; \forall \hat{k} \neq \hat{j}; \forall n = 0, \dots, N_{\hat{k}} \neq n_{\hat{k},CC}; \forall o = 1, \dots, N_{\hat{j}} \neq n_{\hat{j},CC}; \forall m \in F_{n\hat{k}} \cap F_{o\hat{j}} \quad (10)$$

$$\delta_{\hat{k}njom} + \delta_{\hat{j}o\hat{k}nm} \leq 1 + Z(2 - \phi_{\hat{j}om} - \phi_{\hat{k}nm})$$

$$\delta_{\hat{k}njom} + \delta_{\hat{j}o\hat{k}nm} \geq 1 - Z(2 - \phi_{\hat{j}om} - \phi_{\hat{k}nm})$$

$$\forall \hat{j}; \forall \hat{k} \neq \hat{j}; \forall n = 0, \dots, N_{\hat{k}} \neq n_{\hat{k},CC}; \forall o = 1, \dots, N_{\hat{j}} \neq n_{\hat{j},CC}; \forall m \in F_{n\hat{k}} \cap F_{o\hat{j}} \quad (11)$$

$$\sum_{m \in F_{nj}} \phi_{jnm} \leq 1 + Z(1 - \xi_j)$$

$$\sum_{m \in F_{nj}} \phi_{jnm} \geq 1 - Z(1 - \xi_j)$$

$$\forall \hat{j}; \forall n = 0, \dots, N_{\hat{j}} \neq n_{\hat{j},CC} \quad (12)$$

The start date of operation o of virtual charge \hat{j} cannot be before the start date of operation n of charge \hat{k} plus operation time of \hat{k} plus the respective post- and pre-operation times if operation o of charge \hat{j} is processed after operation n of charge \hat{k} on the same facility m (equation 9). For the reverse sequence the equivalent relationship (10) holds. One of the sequences must be chosen if operations o and n of charges \hat{j} and \hat{k} , respectively, are allocated to the same facility m (equation 11). Each operation must be allocated to exactly one of the required facilities (equation 12). Equations (9) and (10) are relevant only for facilities m that can perform operations (n, \hat{k}) and (o, \hat{j}) .

The formulation for the cranes is analogous; the cranes are represented as facilities like the machines (note that the formulation allows multiple operations of a charge on the same facility). The sum of post-operation time and pre-operation time in (9) and (10) is replaced by the time for the positioning of the crane.

Routing of the charges at the facilities (Operation \rightarrow crane or crane \rightarrow subsequent operation)

$$x_{jn} + A_{jnm} + w_{j,n+1} \leq x_{j,n+1} + Z(1 - \phi_{jnm})$$

$$x_{jn} + A_{jnm} + w_{j,n+1} \geq x_{j,n+1} - Z(1 - \phi_{jnm})$$

$$\forall \hat{j}; \forall n = 1, \dots, n(\hat{j}, CC) - 2, n(\hat{j}, CC) + 1, \dots, N_{\hat{j}}; \forall m \in F_{n\hat{j}} \quad (13)$$

$$w_{jn} \leq W_{jn}^{Max} \quad \forall \hat{j}; \forall n = 1, \dots, N_{\hat{j}} \quad (14)$$

Equation (13) relates the start and finish date of operation n of charge \hat{j} on facility m and the start date of the next operation. The formulation does not distinguish between the sequence operation \rightarrow crane and crane \rightarrow subsequent operation. The equation is relevant only for the facility for which the allocation variable is 1 (and thus for virtual charges that are

selected; see (12)). The transport to the continuous caster and the casting operation must be formulated differently (see below). The waiting time can be limited due to technical reasons (temperature of the liquid steel) (equation 14).

Routing of the charges from and to the continuous casters

Virtual charges are not distinguished at the continuous casters. Thus the routing constraints (analogous to (13)) are equations (15) (routing crane \rightarrow continuous caster) and (16) (routing continuous caster \rightarrow subsequent crane).

$$\begin{aligned} x_{\hat{j},n(\hat{j},CC)-1} + A_{\hat{j},n(\hat{j},CC)-1,m} + w_{\hat{j},n(\hat{j},CC)} &\leq x_j^{CC} + Z(2 - \phi_{\hat{j},n(\hat{j},CC)-1,m} - \xi_{\hat{j}}) \\ x_{\hat{j},n(\hat{j},CC)-1} + A_{\hat{j},n(\hat{j},CC)-1,m} + w_{\hat{j},n(\hat{j},CC)} &\geq x_j^{CC} - Z(2 - \phi_{\hat{j},n(\hat{j},CC)-1,m} - \xi_{\hat{j}}) \end{aligned} \quad \forall \hat{j}; \forall \hat{j} \in C_j; \forall m \in F_{n(\hat{j},CC)-1,\hat{j}} \quad (15)$$

$$\begin{aligned} x_j^{CC} + a_j^{CC} + w_{\hat{j},n(\hat{j},CC)+1} &\leq x_{\hat{j},n(\hat{j},CC)+1} + Z(1 - \xi_{\hat{j}}) \\ x_j^{CC} + a_j^{CC} + w_{\hat{j},n(\hat{j},CC)+1} &\geq x_{\hat{j},n(\hat{j},CC)+1} - Z(1 - \xi_{\hat{j}}) \end{aligned} \quad \forall \hat{j}; \forall \hat{j} \in C_j \quad (16)$$

Supply of scrap to the converter

$$\begin{aligned} x_{\hat{j}0} + A_{\hat{j}0m} + w_{\hat{j},n(\hat{j},Conv)} &\leq x_{\hat{j},n(\hat{j},Conv)} + Z(1 - \phi_{\hat{j}0m}) \\ x_{\hat{j}0} + A_{\hat{j}0m} + w_{\hat{j},n(\hat{j},Conv)} &\geq x_{\hat{j},n(\hat{j},Conv)} - Z(1 - \phi_{\hat{j}0m}) \end{aligned} \quad \forall \hat{j}; \forall m \in F_{0\hat{j}} \quad (17)$$

$n=0$ denotes the transport of the scrap to the converter. The start date of this transport $x_{\hat{j}0}$ plus the transportation time plus the waiting time for the converter operation ($n(\hat{j}, Conv)$ denotes converter operation) must be equal to the start date at the converter. The equation is only relevant for the crane that performs the transport.

Sequence of the charges at the ladles

$$\begin{aligned}
 x_{\hat{j}, N_{\hat{j}}} + A_{\hat{j}, N_{\hat{j}}, c} + w_{\hat{j}, N_{\hat{j}}+1} &\leq x_{\hat{k}, o(\hat{k}, Conv)} + L_{\hat{k}, o(\hat{k}, Conv), m} + Z(5 - \phi_{\hat{j}, N_{\hat{j}}, c} - \phi_{\hat{k}, o(\hat{k}, Conv), m} - \hat{\phi}_{\hat{j}p} - \hat{\phi}_{\hat{k}p} - \hat{\delta}_{\hat{j}\hat{k}p}) \\
 x_{\hat{j}, N_{\hat{j}}} + A_{\hat{j}, N_{\hat{j}}, c} + w_{\hat{j}, N_{\hat{j}}+1} &\geq x_{\hat{k}, o(\hat{k}, Conv)} + L_{\hat{k}, o(\hat{k}, Conv), m} - Z(5 - \phi_{\hat{j}, N_{\hat{j}}, c} - \phi_{\hat{k}, o(\hat{k}, Conv), m} - \hat{\phi}_{\hat{j}p} - \hat{\phi}_{\hat{k}p} - \hat{\delta}_{\hat{j}\hat{k}p}) \quad (18) \\
 \forall \hat{j}; \forall \hat{k} \neq \hat{j}; \forall c \in F_{N_{\hat{j}}, \hat{j}}; m \in F_{o(\hat{k}, Conv), \hat{k}}; p \in \{\text{ladles}\};
 \end{aligned}$$

$$\begin{aligned}
 \sum_p \hat{\phi}_{\hat{j}p} &\geq 1 - Z(1 - \xi_{\hat{j}}) \\
 \sum_p \hat{\phi}_{\hat{j}p} &\leq 1 + Z(1 - \xi_{\hat{j}})
 \end{aligned}
 \quad \text{for all } \hat{j} \quad (19)$$

$$\begin{aligned}
 \hat{\delta}_{\hat{j}\hat{k}p} + \hat{\delta}_{\hat{k}\hat{j}p} &\geq 1 - Z(2 - \hat{\phi}_{\hat{j}p} - \hat{\phi}_{\hat{k}p}) \\
 \hat{\delta}_{\hat{j}\hat{k}p} + \hat{\delta}_{\hat{k}\hat{j}p} &\leq 1 + Z(2 - \hat{\phi}_{\hat{j}p} - \hat{\phi}_{\hat{k}p})
 \end{aligned}
 \quad \forall \hat{j}, \hat{k} \neq \hat{j}; \forall p \quad (20)$$

Equation (18) guarantees that ladle rework after charge \hat{j} and the subsequent transport of the ladle to the converter where the next charge on this ladle (with index \hat{k}) is scheduled are finished before the ladle can be used again (tapping of the converter). Index $N_{\hat{j}}$ denotes the last operation on charge \hat{j} (transport after ladle rework), $w_{\hat{j}, N_{\hat{j}}+1}$ is the waiting time of the ladle before tapping the next charge (note that operation $N_{\hat{j}}+1$ on charge \hat{j} does not exist). $L_{\hat{k}, o(\hat{k}, Conv), m}$ denotes the time from the start of the converter operation to the start of tapping for charge \hat{k} on converter m . Equations (19) allocate each charge to exactly one ladle; equations (20) are the sequencing constraints for charges that are allocated to the same ladle.

Limited hot metal availability

$$\sum_{\hat{j} \in C_j} H_{\hat{j}} \xi_{\hat{j}} + \sum_{\hat{k} \in C_j} H_{\hat{k}} \delta_{\hat{k}1, \hat{j}1, Deslag} \leq E^{-1}(x_{\hat{j}1}) \quad \text{for all } j \quad (21)$$

The cumulative hot metal demand for charge j (the virtual charge that is selected) and all its predecessors (left side of equation (21)) must not exceed the cumulative supply of hot

metal at the start date of this charge (right side of (21)). The hot metal is required when the deslagging operation starts, which is operation 1 for each charge ($m = Deslag$ denotes deslagging). The second term of the left side of equation (21) totals the hot metal demand of all virtual charges that are started earlier than \hat{j} . Note that this implies that these virtual charges are actually selected (equations (11) and (12)).

The right side of equation (21) is linear only if $E(t)$ (the cumulative hot metal supply as a function of the time t) is linear. This is the case for the relevant planning horizon of 72 hours (see section 2). The random variations require a safety stock that reduces the planned hot metal supply $E(t)$.

5.2.2 Objective function

The objective function is the weighted sum of the following terms:

- Duration of the cast breaks = $\sum_j \beta_j B_j + \sum_j b_j^{add}$, multiplied by the costs per time unit C^{Setup} and C^{Break} , respectively.
- Total flow times, consisting of three components: (1) flow time of the charge from the start date at the converter to the finish date at the continuous caster (cost coefficient C^{Charge}); (2) flow time of the scrap from the start date of transportation to the start date at the converter (cost coefficient C^{Scrap}); (3) flow time of the hot metal from the start date of transportation to the start date at the converter (cost coefficient C^{Metal}).
- Due dates of the charges. We define a target due date D_j and cost coefficients for positive and negative due date deviations. In the current implementation $D_j = 0 \quad \forall j$.

- Changes of the relative casting speed $d_j^{CC^-}, d_j^{CC^+}$. The cost coefficients for negative and positive deviations (C^{Speed}) are assumed to be equal.

The route preferences can be expressed as weights for each virtual charge \hat{j} . This is not included here. The decisions on the route are based on rules that cannot be expressed exactly in the model.

The objective function is:

$$\begin{aligned}
 & C^{Setup} \sum_j \beta_j B_j + C^{Break} \sum_j b_j^{add} + C^{Charge} \sum_j \left(a_j^{CC} + |C_j| x_j^{CC} - \sum_{\hat{j} \in C_j} x_{\hat{j}, n(\hat{j}, Conv)} \right) + \\
 & C^{Metal} \sum_{\hat{j}} \left(x_{\hat{j}, n(\hat{j}, Conv)} - x_{\hat{j}, n(\hat{j}, Deslag)} \right) + C^{Scrap} \sum_{\hat{j}} \left(x_{\hat{j}, n(\hat{j}, Conv)} - x_{\hat{j}, n(\hat{j}, Scrap)} \right) + \\
 & C^{DD+} \sum_j f_j^+ + C^{DD-} \sum_j f_j^- + C^{Speed} \sum_j (d_j^+ + d_j^-) \\
 & \rightarrow Min!
 \end{aligned} \tag{22}$$

$n(\hat{j}, Conv), n(\hat{j}, Deslag), n(\hat{j}, Scrap)$ denote, respectively, the index of converter operation, deslagging (index=1) and transport of the scrap (index=0). Note that all start dates of virtual charges that are not selected are not subject to constraints. Thus these variables must be constrained so that the flow time components of these charges are set to zero. The following constraints are added:

$$x_{\hat{j}, n(\hat{j}, Deslag)} \leq x_{\hat{j}, n(\hat{j}, Conv)} \quad \text{for all } \hat{j} \tag{23}$$

$$x_{\hat{j}, n(\hat{j}, Scrap)} \leq x_{\hat{j}, n(\hat{j}, Conv)} \quad \text{for all } \hat{j} \tag{24}$$

$$x_{\hat{j}, n(\hat{j}, Conv)} \leq x_j^{CC} \quad \forall j; \forall \hat{j} \in C_j \tag{25}$$

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3 For the virtual charges that are actually selected these constraints are redundant. Note
4 that the first flow time component in (22) is the flow time of the virtual charge that is selected
5 since all other $x_{\hat{j},n(\hat{j},Conv)}$ are set to x_j^{CC} in the optimization (constraint (25)).
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10 11 **6 Description of the hierarchical scheduling system**

12 13 **6.1 Overview**

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15 The proposed and implemented scheduling system is a hierarchical system consisting
16 of three planning levels.
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- 18 • Level 1: Scheduling the casts on the continuous casters: determining the
19 starting and finish date and the casting speed for all casting operations.
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- 21 • Level 2: Detailed scheduling of the charges on all facilities: allocation,
22 sequencing and preliminary timing.
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- 24 • Level 3: LP-improvement: adjusting of timing and casting speed of all charges
25 and casts.
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37 Levels 1 and 2 can be interpreted as a heuristic that that determines the binary
38 variables of the MILP model of section 5 and preliminary values of continuous variables.
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40 Level 3 determines the final values of the continuous variables, taking the binary variables as
41 fixed.
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46 In the next sections we describe these planning levels in detail.
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53 54 **6.2 Detailed description of the planning levels**

55 56 **6.2.1 Scheduling the continuous casters**

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58 Based on the cast topology, this level creates a feasible schedule for the continuous
59 casters (termed *CC schedule*) and thus is similar to a finite loading procedure. The decision
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3 variables are the start dates x_j^{CC} and casting times a_j^{CC} for all casting operations. They have to
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5
6 be determined such that the CC schedule is feasible with respect to the upstream facilities and
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8 hot metal availability and the makespan is minimized. The planning process is performed
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10 primarily for *casts*; that is, special emphasis is put on the continuity constraints on the
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12 continuous casters. This decision problem is solved heuristically by decomposing the problem
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14 into the sub-problems (1) determining the casting speed (equivalently: the casting times) over
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16 time for given start dates of the casts, (2) determining the start dates of the casts for a given
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18 casting speed. These sub-problems are solved iteratively. The procedure is as follows
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22 (figure 4):
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32 Figure 4: Algorithm for scheduling the continuous casters
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37 In the following sections we describe the feasibility check for a CC schedule that is
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39 required in step 1 and step 2; then we describe the algorithms for step 2 and step 3 of the
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41 procedure of figure 4.
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50 *Step 1: Feasibility check for a CC schedule*

51 The feasibility checks against capacities and against hot metal are based on
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53 Input/Output Control (see Belt 1976, Wight 1974) and cumulative quantities of hot metal
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55 supply/demand, respectively. Both feasibility checks are based on similar logic:
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- 57 • Hot metal: The cumulative availability of hot metal over time is known.
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59 Planned lead times for the charges are derived from the operation times and
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planned waiting times of the operations upstream from the continuous casters.

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3 Thus the cumulative requirements of hot metal over time can be calculated for
4 each CC schedule and can be checked against the cumulative availability of
5 hot metal. A CC schedule is feasible with respect to hot metal if cumulative
6 requirements do not exceed cumulative availability of hot metal at any time.
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12 • Capacities are aggregated to capacity groups (aggregate converter capacity,
13 etc.), the available capacity over time is known. An appropriate amount of
14 disaggregation slack can be considered here. Since operation times are
15 sequence-independent, there is no danger of infeasible disaggregation due to
16 the allocation uncertainty (for this problem, see Grunow et al. 2003, p. 92 ff.).
17 It is assumed that available capacity can be cumulated over time (like
18 material), but capacity is assumed to decay exponentially over time if it is not
19 used (that is, capacity can be stored for a limited time), which is a rather crude
20 heuristic. For each CC schedule, the cumulative capacity requirements for the
21 capacity groups can be calculated from the operation times and the planned
22 lead times of the charges. A CC schedule is feasible with respect to a certain
23 capacity group if cumulative requirements do not exceed cumulative available
24 capacity at any time.
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46 *Step 2: Determining the casting speed*

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49 For given start dates of the casts, this step determines the extent to which the casting
50 speed has to be reduced (starting from the target value) in order to obtain feasibility. The
51 algorithm divides the planning horizon into short periods (e.g., 15 minutes) and consecutively
52 determines the casting speed for each period (forward pass). For each period the casting speed
53 is set to the maximum value that achieves feasibility. Figure 5 describes the algorithm in
54 detail.
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Figure 5: Determination of the casting speed

Step 3: Determining the start dates for the casts

For given resource availability and casting speed of each cast, the algorithm sorts the casts according to the priorities (from the cast topology) and consecutively schedules the casts at the earliest start date. If necessary, the casting speed can be reduced in order to obtain feasibility. The algorithm is presented in figure 6.

Figure 6: Determination of the start dates of the casts

After step 2 and 3 (figure 4) are repeated several times and the result is sufficiently stable, the casting speeds can vary substantially from period to period. This is undesirable (see objective function (22)), so the last step is smoothing the casting speed in order to avoid large short-term variations.

The algorithm avoids cast breaks whenever possible, except for charges where a setup is necessary due to technological reasons and for casts that already have been started; in this case a cast break can be unavoidable.

6.2.2 Detailed scheduling of the charges

This is the core part of the scheduling algorithm. Based on the planned start dates of the charges on the continuous casters, this planning level determines the allocation of the charges to facilities, the production sequences at the facilities and preliminary start and finish dates. The algorithm is a rule-based sequential scheduling heuristic that can be considered as

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3 an extension of the well-known Giffler/Thompson algorithm (Giffler/Thompson 1960). The
4 extensions encompass four topics: (1) parallel facilities, (2) route preferences (figure 2),
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6 (3) multiple resource constraints (facilities, ladles and hot metal), (4) frozen decisions (e.g.,
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8 the allocation of charges to converters must be frozen several hours in advance because the
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10 availability of material and the transports have to be planned). The continuity constraints on
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12 the continuous casters are considered roughly in a subsequent planning phase. Consequently,
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14 the algorithm requires rules for the allocation of the charges and for sequencing. The
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16 allocation rules decide whether a charge is allocated according to the standard route or
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18 according to an alternative route (see figure 2); in the scheduling algorithm (figure 7) they
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20 determine the *preferred facility*. The route preferences are modelled as time limits; that is, the
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22 decision maker is indifferent between the standard route and a delay of x minutes and the
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24 alternative route without delay. The sequencing rules usually give priority to the charge with
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26 the longest waiting time and also consider availability of the relevant resources, e.g., ladles.
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28 This rule base (allocation and sequencing rules) contains comprehensive expert knowledge
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30 and has been developed in cooperation with the planners over several years. The details are
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32 beyond the scope of this paper.
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41 The planning algorithm consists of two phases that are repeated until the result is
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43 sufficiently stable:
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- 45 • Backward scheduling, starting with the predefined start dates on the continuous
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47 casters.
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- 49 • Forward scheduling, starting as early as possible, where the starting sequence
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51 of the charges results from backward scheduling.
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55 Figure 7 depicts the backward scheduling algorithm.
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Figure 7: The backward scheduling algorithm

The algorithm for forward scheduling is basically the same with some modifications regarding the determination of the preferred facility. It requires the transformation of the backward priorities from the route preferences to forward priorities. This is performed by a heuristic that is beyond the scope of the paper. The allocation decisions also consider the allocations from backward scheduling; this is an element of the rule base mentioned above. If forward scheduling results in an infeasible solution (cast breaks), forward scheduling is repeated based on longer casting times until the result is (at least nearly) feasible. Small infeasibilities are corrected by LP improvement which is described next.

6.2.3 *Adjustment of timing and casting speed*

Once the allocation and sequencing decisions are made, the simultaneous determination of start and finish dates of the operations, including the casting speed for each charge, can be formulated as an LP model as in Tang et al. (2000). This improvement of the schedule is sensible because the previous planning steps do not consider the scheduling decisions for the charges and the continuity constraints for the continuous casters simultaneously, which can result in suboptimal or even infeasible schedules (short cast breaks that have to be avoided).

Next we present the LP model.

6.2.3.1 Variables and Parameters

The variables are identical to the continuous variables of the MILP model described in section 5. The binary variables are determined by scheduling level 2, and these decisions are represented as additional parameters as follows:

One route (virtual charge) is selected for each charge j (exactly one $\xi_j \in C_j = 1$). Therefore the LP model schedules charges j ; the data for charge j are taken from the respective virtual charge \hat{j} .

Each operation n of charge j is allocated to one facility (exactly one $\phi_{jnm} \in F_{nj} = 1$); each charge j is allocated to one ladle (exactly one $\hat{\phi}_{jp} = 1$ for each j). $m(j, n)$ denotes the facility that performs operation n on charge j . Equivalently, $p(j)$ denotes the ladle that is allocated to charge j .

The allocation variables ϕ_{jnm} and the sequence variables $\delta_{jn,ko,m}$ are fixed, thus the sequence of the operations on each facility m is known. Let $V(j, n, m)$ denote the predecessor of operation n of charge j on facility m , defined in terms of operation and charge; e.g., $V(j, n, m) = ko$ (operation o of charge k). Equivalently, let $S(j, n, m)$ denote the successor of operation n of charge j on facility m , again defined in terms of charge and operation. $S(j, p)$ denotes the successor of charge j on the respective ladle $p(j)$.

For the cast breaks an LP relaxation is applied: The break variables β_j and the additional idle time b_j^{add} are replaced by the variable b_j that denotes the duration of a cast break before charge j on the continuous caster if no cast break is scheduled.

6.2.3.2 Formulation of the LP model

Constraints

Since the setup variables β_j are determined and b_j is defined as described above, equations (1) and (2) are replaced by

$$x_{V(j,CC)}^{CC} + a_{r(j,CC)}^{CC} + b_j = x_j^{CC} \quad \text{for all } j \quad (26)$$

$$x_{V(j,CC)}^{CC} + a_{r(j,CC)}^{CC} + b_j + U_j = x_j^{CC} \quad \text{for all } j \quad (27)$$

The cast break time b_j is the difference between start date of charge j and finish date of its predecessor, considering the time for tundish change if this is relevant.

Constraints (3) to (7), which are related to the continuous casters, remain unchanged. The other constraints can be derived from the MILP model and formulated as follows:

Start date of operations on the facilities (production sequence as seen by the facility)

Equations (9) and (10) are replaced by:

$$x_{kn} + A_{k,n,m(k,n)} + P_{k,n,m(k,n)} + R_{j,o,m(j,o)} \leq x_{jo}$$

operation $(j,o) = S(k,n,m(k,n))$

$$\forall m \notin \{CC\}; \text{ for all operations } (n,k) \text{ allocated to } m \quad (28)$$

These constraints relate the start dates of two successive operations on facility m . Operation k of charge n is the immediate predecessor of operation o on charge j .

Routing of the charges at the facilities (operation \rightarrow crane or crane \rightarrow subsequent operation)

Equation (13) and (14) are replaced by

$$x_{jn} + A_{j,n,m(j,n)} + w_{j,n+1} = x_{j,n+1} \quad \forall j; \forall n = 1, \dots, N_j - 1 \quad (29)$$

$$w_{jn} \leq W_{jn}^{Max} \quad \forall j; \forall n = 1, \dots, N_j \quad (30)$$

These constraints relate the start dates of the successive operations of each charge j at the respective facilities. The constraints are the same for the route from and to the continuous caster; hence equations (15) and (16) are replaced by (29) and (30). For the casting operations, $A_{j,n,m(j,n)}$ is replaced by a_j^{CC} , x_{jn} is replaced by x_j^{CC} .

Supply of scrap to the converter

Equation (17) is replaced by:

$$x_{j0} + A_{j0m} + w_{j,n(j,Conv)} = x_{j,n(j,Conv)}$$

$$\forall j; m = \text{crane transporting scrap for } j \text{ to the converter} \quad (31)$$

For the description, see equation (17).

Sequence of the charges at the ladles

Equations (18)-(20) are replaced by:

$$x_{j,N_j} + A_{j,N_j,c} + w_{j,N_j+1} = x_{S(j,p),o} + L_{S(j,p),o}$$

$$\forall j; c = \text{crane performing the transport operation } N_j; \quad (32)$$

o = Index of converter operation of charge $S(j, p)$

This equation guarantees that ladle rework after charge j and the subsequent transport of the ladle to the converter where the next charge on this ladle (with index $S(j,p)$) is scheduled are finished before the ladle can be used again (tapping of the converter for charge $S(j,p)$). $L_{S(j,p),o}$ denotes the time from start of the converter operation to the start of tapping for charge $S(j,p)$.

Limited hot metal availability

The starting sequence of the charges is fixed. Thus the cumulative requirements of hot metal for each charge j and all charges that are started earlier is a constant. The earliest start date of charge j is the date where this constant is less than or equal to the available amount of hot metal. Thus equation (21) is replaced by:

$$x_{j1} \geq E^{-1}\left(H_j + \sum_{k \in \text{Pre}(j)} H_k\right) \quad \forall j \quad (33)$$

$\text{Pre}(j)$ denotes the set of all charges that are started earlier than charge j . Note that in contrast to (21), linearity of $E(t)$ need not be assumed.

Objective function

The objective function is derived from (22) by fixing the relevant j and substituting $\sum_j b_j$ for the total duration of the cast breaks:

$$\begin{aligned} & C^{\text{Break}} \sum_j b_j + C^{\text{Charge}} \sum_j (x_j^{\text{CC}} + a_j^{\text{CC}} - x_{j,n(j,\text{Conv})}) + \\ & C^{\text{Metal}} \sum_j (x_{j,n(j,\text{Conv})} - x_{j,n(j,\text{Deslag})}) + C^{\text{Scrap}} \sum_j (x_{j,n(j,\text{Conv})} - x_{j,n(j,\text{Scrap})}) + \\ & C^{\text{DD}+} \sum_j f_j^+ + C^{\text{DD}-} \sum_j f_j^- + C^{\text{Speed}} \sum_j (d_j^+ + d_j^-) \\ & \rightarrow \text{Min!} \end{aligned} \quad (34)$$

Objective function (34) and constraints (26), (27), (3) to (7), (28), (29), (30), (31), (32) and (33) are the LP model that yields the final schedule. The model encompasses about 10000 variables and 8000 constraints for a planning horizon of 72 hours.

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3 The computational time for the algorithm is about 25 seconds, including 15 seconds
4 for the LP, using an interior point solver (as of September 2007). Figure 8 depicts a schedule
5 for the steel plant as it is displayed for the planner.
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18 Figure 8: Schedule displayed for the planner
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24 **7 Project and implementation**

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27 The project was motivated by a request to support the manual planning process.
28 Project phase 1 (1995-1998) encompassed the concept development and programming of a
29 prototype version. The essential design decision was to design a detailed scheduling system.
30 The alternative would have been a planning system that determines planned start and finish
31 dates and leaves detailed scheduling (sequencing) to the dispatchers, but this seemed
32 inappropriate here. Phase 2 (1999-2001) encompassed the evaluation of the concept and the
33 investment decision by the company. Phase 3 (2002 to June 2005) encompassed programming
34 of the final version and implementation. The software was developed by a small software
35 vendor; the optimization engine was designed and programmed mainly by a consultant
36 specialized in optimization and production planning.
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51 Realized benefits: Two years after implementation, the system is accepted and
52 indispensable for the planners. The transparency of the schedule was improved substantially,
53 especially when control is transferred to the personnel of the next shift. The optimization
54 engine is actually used by the planners, although manual adjustments of the schedules are
55 necessary. The increase in output is difficult to assess because at the time of implementation
56 the output increased by some 20% due to substantial capacity expansions, making it virtually
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3 impossible to isolate the effect of the scheduling system. Optimization results have been
4 compared to the actual production volumes before the implementation, but this is not a valid
5 comparison because the optimization results cannot reflect the disturbances and repeated
6 rescheduling that occurs in practice. From a number of observations that cannot be described
7 here in detail we estimate that the scheduling system improves the output by about 1%.
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15 The following managerial implications can be derived from the project: (1) Despite
16 the extensive literature on scheduling in different industries, new methods even for schedule
17 generation can be necessary in special cases such as the steel industry. (2) A computerized
18 scheduling system heavily intervenes in a manufacturing process that has been working for
19 decades. Integrating the system into the problem-solving process of the planners and into the
20 organization (decision competences of the dispatchers at different facilities) is extremely
21 important. (2) This takes time, and close cooperation with the potential users is decisive for
22 success. (3) Implementation is a complex process and requires great effort on the part of the
23 project managers. For two months a project manager was available on the shop floor and
24 available by phone for three more months. (4) Continual improvements of the planning rules
25 are necessary after implementation. In our case manual adjustments to compensate for
26 inappropriate rules are made (see above), but with decreasing frequency. Adjustments of
27 parameters (including safety margins) are also a part of this improvement process.
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50 **8 Conclusions and research perspectives**

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52 SM-CC scheduling is a complex scheduling problem, partly because of its
53 combinatorial nature, but also because of the technological know-how that is necessary for
54 performing the task. Manual scheduling systems, largely based on experience and informal
55 coordination, can perform well, but reach their limit as the complexity of the manufacturing
56 system increases. Thus computerized scheduling systems are increasingly necessary, but the
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3 research results that are available and mature for practical implementation are very limited at
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5 the moment.
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8 This paper presented a new method for scheduling the steelmaking – continuous
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10 casting process in a complex steel plant with several continuous casters. The approach
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12 performs well for the practical scheduling task, but a number of research topics remain open.
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14 We can classify these topics into (1) modelling and optimization technique and (2) integrating
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16 the model into shop floor organization and human problem solving.
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19 20 *Modelling and optimization technique* 21

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23 The CC scheduling subproblem (level 1 in the planning hierarchy; see section 6.2.1) is
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25 a special case of a finite loading problem that is solved by a simple heuristic. The application
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27 of optimization techniques from project scheduling (Kolisch 1995, Neumann et al. 2001),
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29 scheduling in other process industries (Neumann et al. 2001, Neumann/Schwindt 2003),
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31 combinatorial optimization methods for finite loading (e.g., Hans 2001) or advanced
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33 approaches for this specific problem (Krappinger 2004) might be possible and could provide
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35 better results. Furthermore a hierarchical planning system where the aggregate plans for the
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37 facilities upstream from the continuous casters are disaggregated in order to obtain a feasible
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39 schedule (see, e.g., Grunow et al. 2003) is an interesting alternative. A hierarchical system
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41 with detailed scheduling of the operations (level 2 in the planning hierarchy) as a separate
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43 planning task facilitates the use of scheduling rules that have proven beneficial, but
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45 simultaneous scheduling of all facilities (level 1 and 2 of our approach) to one planning task
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47 (like in Bellabdaoui et al. 2005) is a serious alternative. Integrating the SM-CC scheduling
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49 problem into an integrated planning concept for the steel plant, including the rolling mills, is
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51 an important research topic as well (see Tang et al. 2001).
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58 *Integration into shop floor organization and human problem solving* 59 60

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3 The nine years from the first conceptual study to the implementation of the scheduling
4 software demonstrated that, for successful installation, appropriate integration of the
5 computerized scheduling system into human problem solving and shop floor organization is at
6 least as important as the optimization engine. SM-CC scheduling had been performed
7 manually for decades employing a set of planning rules. Some of these rules reflect
8 technological properties of the process and of the manufacturing system, but there are also
9 rules that simplify the scheduling problem. For instance, a planning logic was in use that
10 divides the manufacturing system into virtual flow lines: From converter x the charges go to
11 ladle furnace y, then to continuous caster z. Material flows from one virtual flow line to the
12 other (which are necessary in order to balance the capacities) follow certain rules as well.
13 Clearly these rules are constraints and are in conflict with optimality of the schedule, but they
14 enable the planners to understand the logic of the schedule: Certain disturbances on the shop
15 floor require *immediate* reaction by the planners (e.g., to avoid a cast break if a charge is
16 delayed), and it is of great importance for the dispatcher to understand the schedule, the
17 interdependencies of the production sequences at different facilities, etc. Little is known in
18 scheduling literature about the extent to which deviations from optimality should be accepted
19 in order to make schedules more transparent and thus to account for the “bounded rationality”
20 of the dispatchers.
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45 The scheduling algorithm implies centralized planning by one decision maker. This is
46 contrary to the informal system where dispatchers or foremen who are responsible for their
47 respective facilities coordinate their local decisions, employing knowledge about their
48 production processes. This raises the question of the extent to which the schedule should be
49 flexible or subject to change by various local decisions makers. Integration of insights on
50 *Distributed Decision Making* (Schneeweiss 2003) might prove beneficial for complex
51 manufacturing systems like the one described in this paper.
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3 ***List of Acronyms***
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6 CC Continuous caster
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9 CS Conditioning stand
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11 LD Linz-Donawitz; denotes the steelmaking process that is used in the steel
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13 plant
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16 LF Ladle furnace
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19 MILP Mixed-integer linear programming
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22 RH Vacuum degassing unit (Ruhrstahl Heraeus process)
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25 SM-CC Steelmaking - continuous casting
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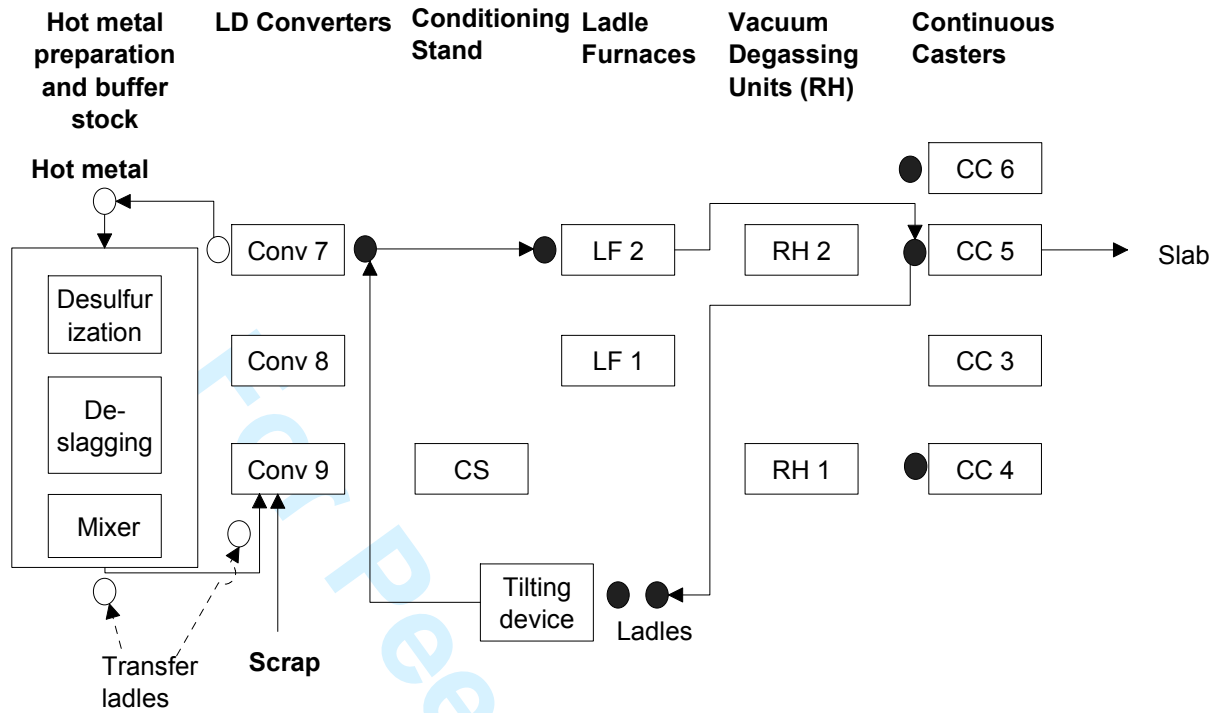


Figure 1: The steelmaking – continuous casting process under consideration

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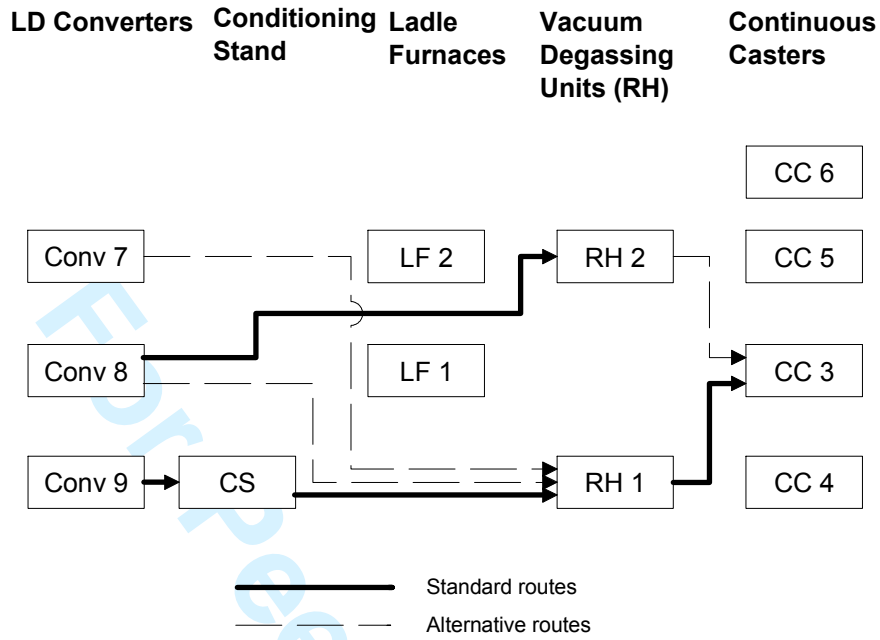
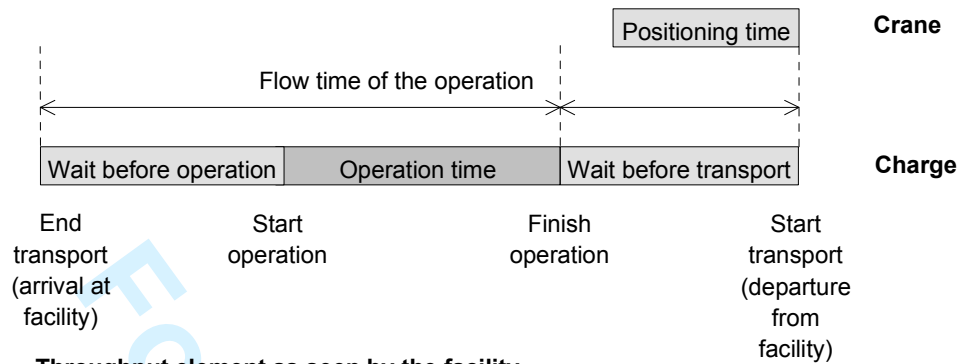


Figure 2: Route preferences for a steel grade (example)

Throughput element as seen by the charge and the crane



Throughput element as seen by the facility

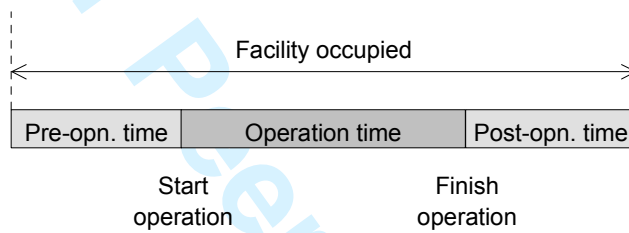


Figure 3: Throughput element of an operation

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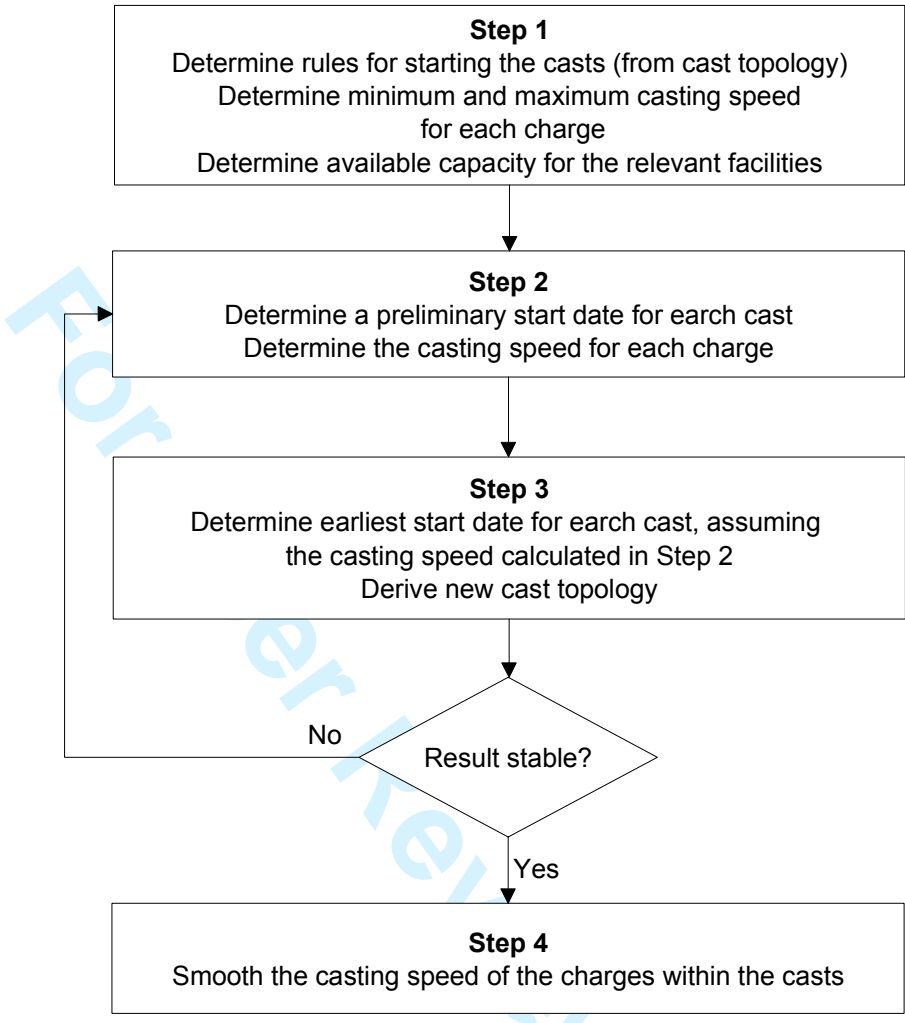


Figure 4: Algorithm for scheduling the continuous casters

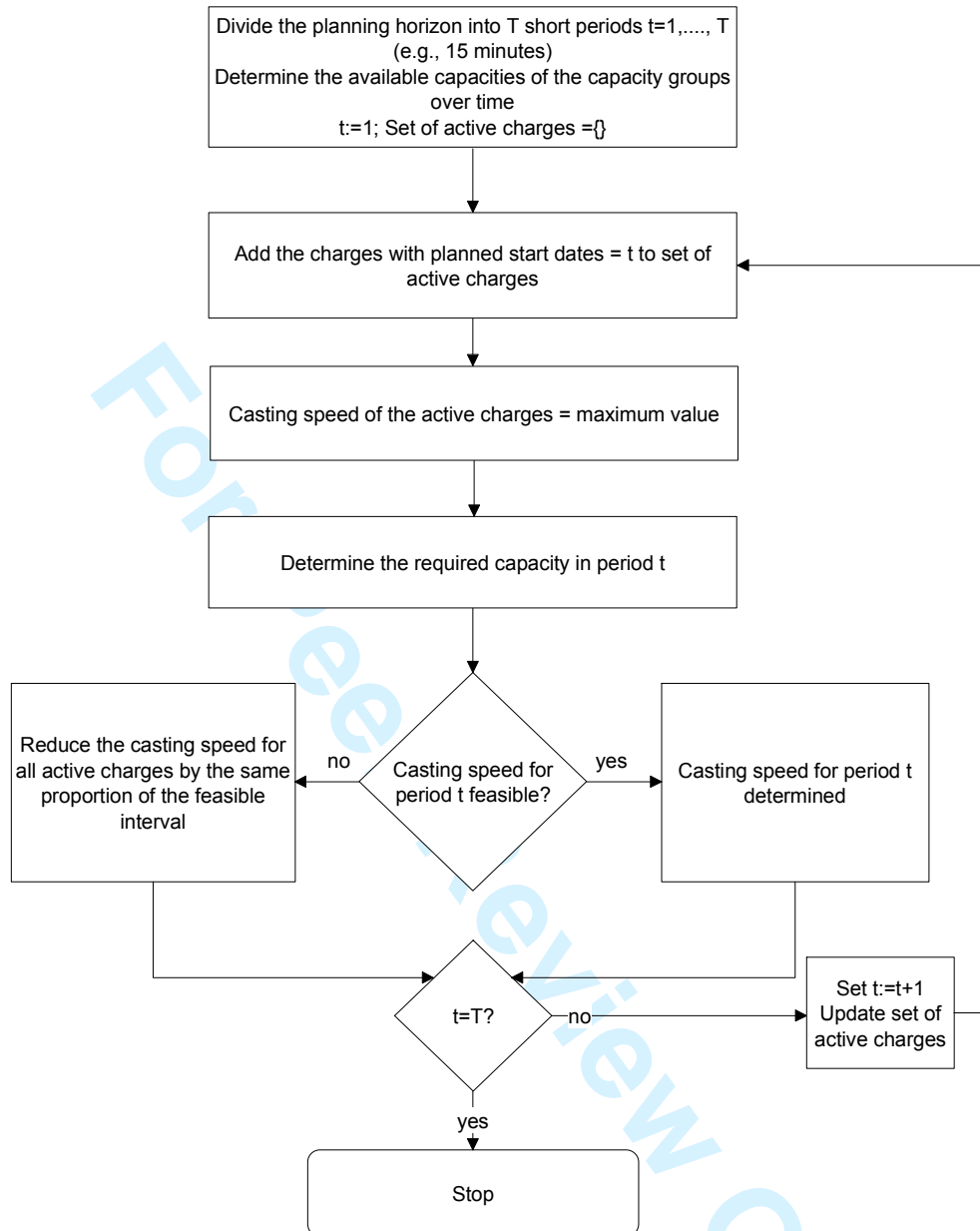


Figure 5: Determination of the casting speed

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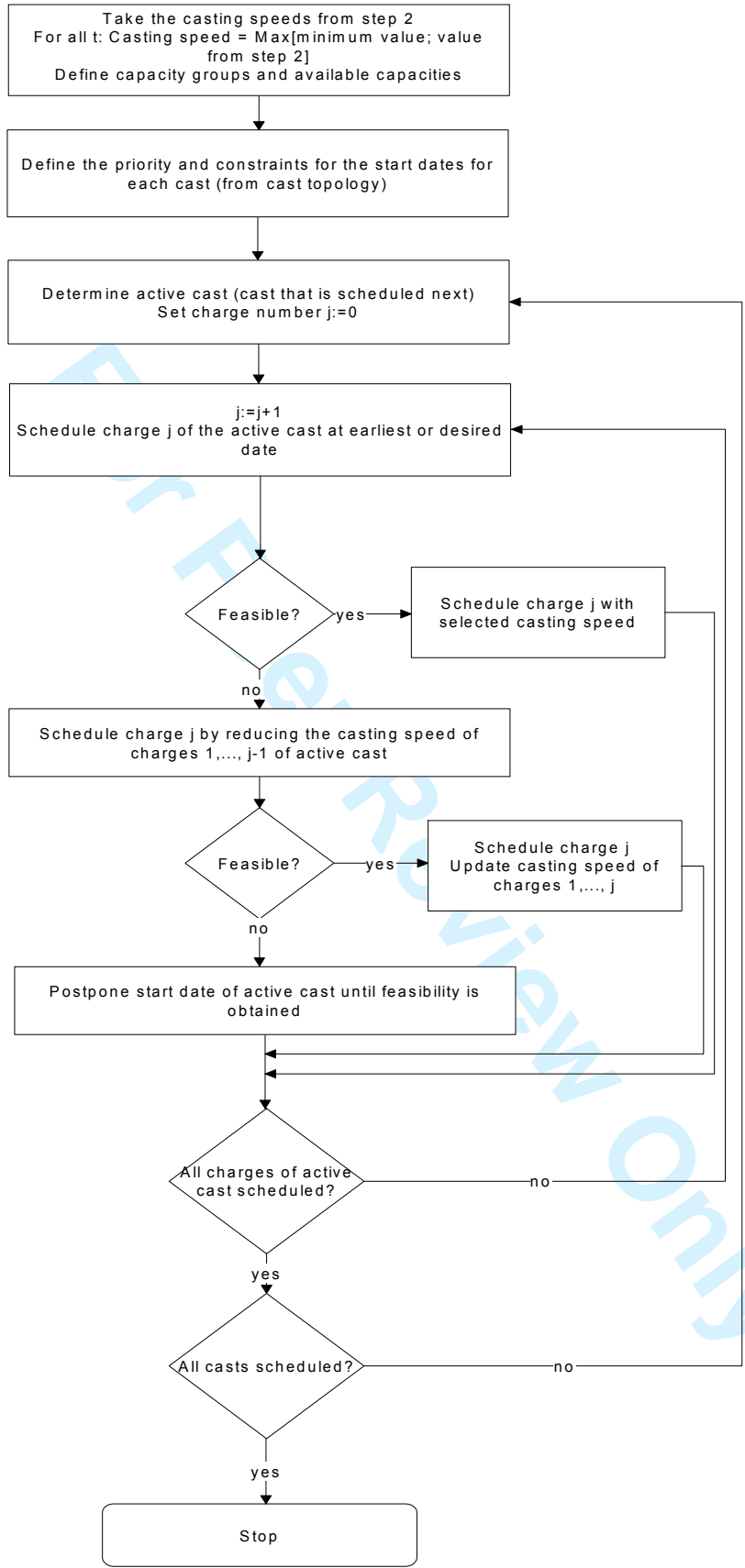


Figure 6: Determination of the start dates of the casts

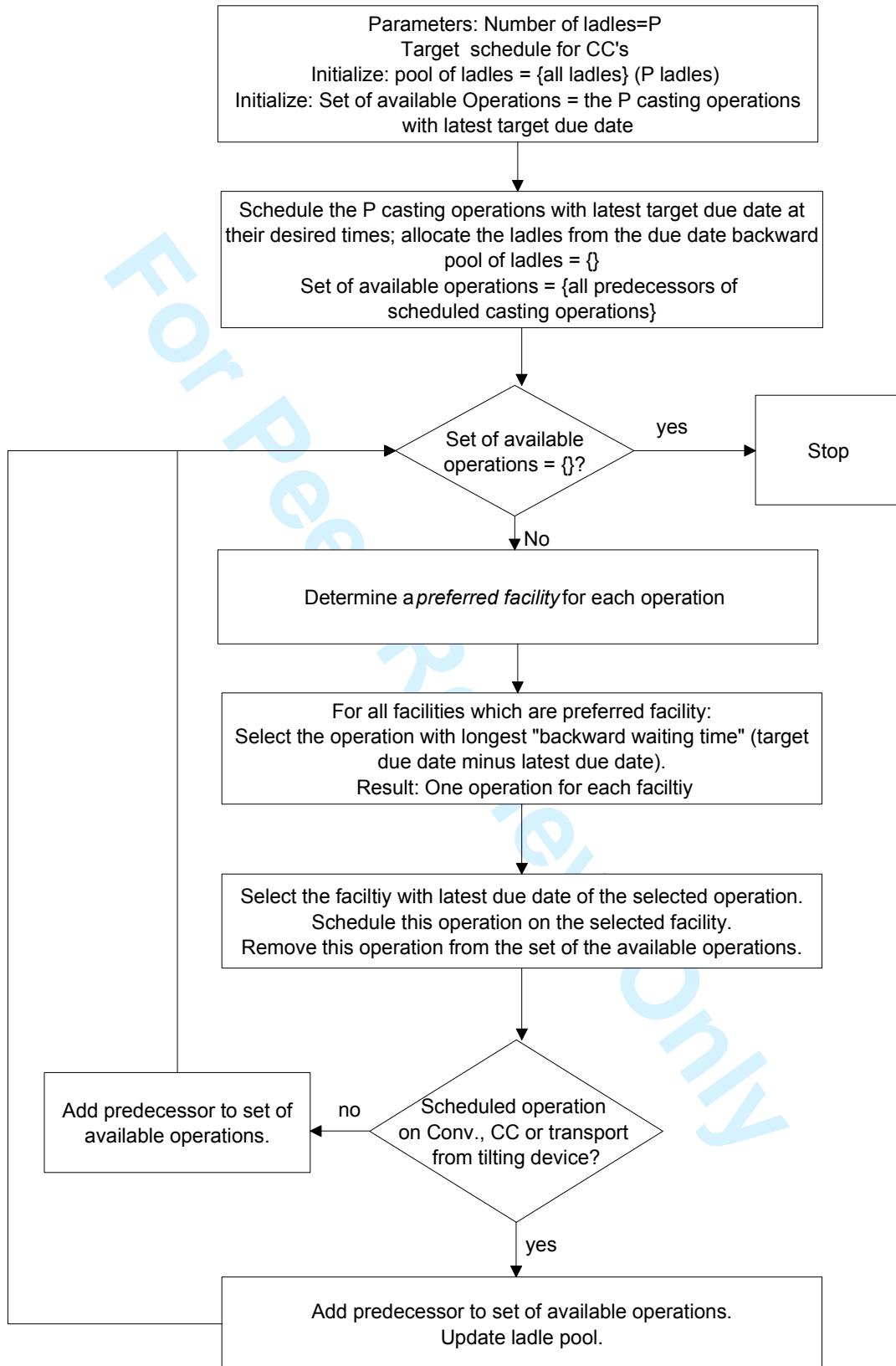


Figure 7: The backward scheduling algorithm

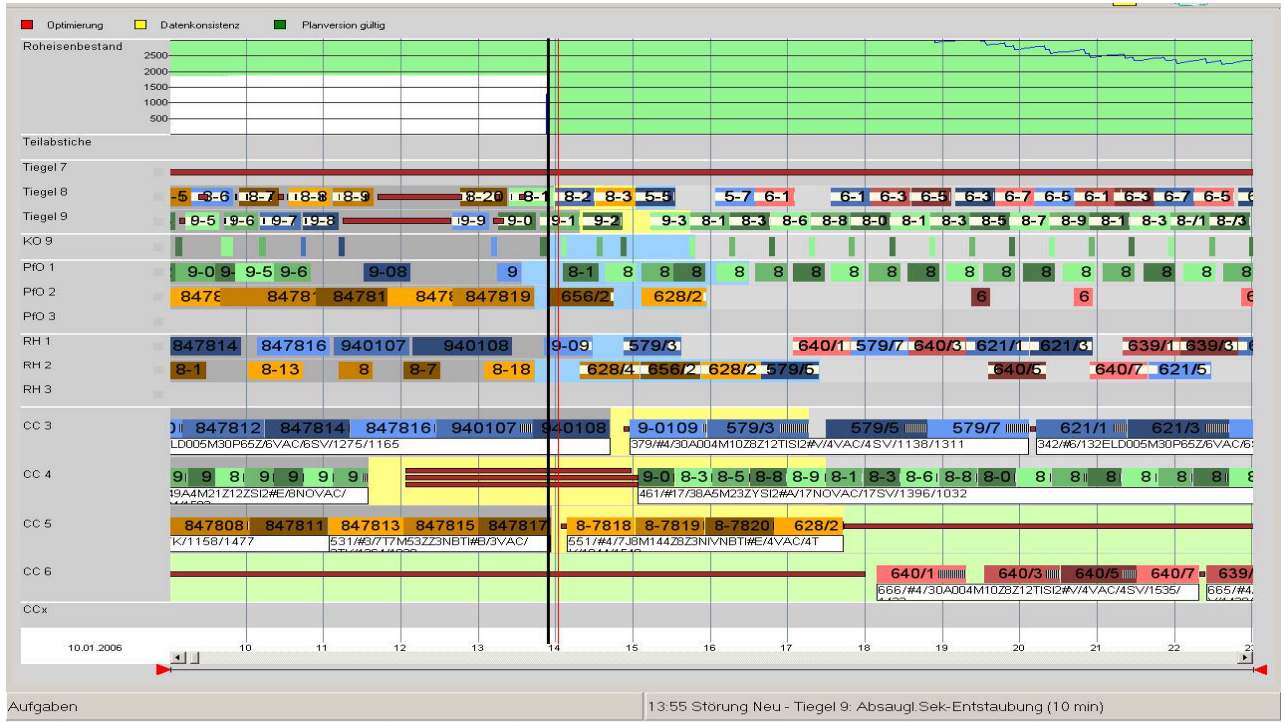


Figure 8: Schedule displayed for the planner