Process control for secondary metallurgy processes
Introduction and general considerations

› Secondary metallurgy processes involve a large variety of complex metallurgical reactions as e.g.

  › Decarburisation

  › Removal of dissolved gases (degassing)

  › Desulphurisation by steel / slag interaction

  › Deoxidation and Alloying

  › Removal of non-metallic inclusions

› The process behaviour and the relevant state variables of the process (temperature and composition of steel and slag) can so far be monitored and controlled only based on spot measurements (T, O, H) as well as analysis of steel and slag samples

› Thus one important topic of R&D work on Secondary metallurgy processes has been and is still the development and application of **dynamic process models for on-line monitoring and control** of the process behaviour

› The presentation gives an overview on results of several selected ECSC and RFCS projects regarding process control for the following topics:

  › Process control of vacuum degassing processes (RH, VD)

  › Process control of stainless steel refining processes (AOD, VOD)

  › Through process control of the complete secondary steelmaking route

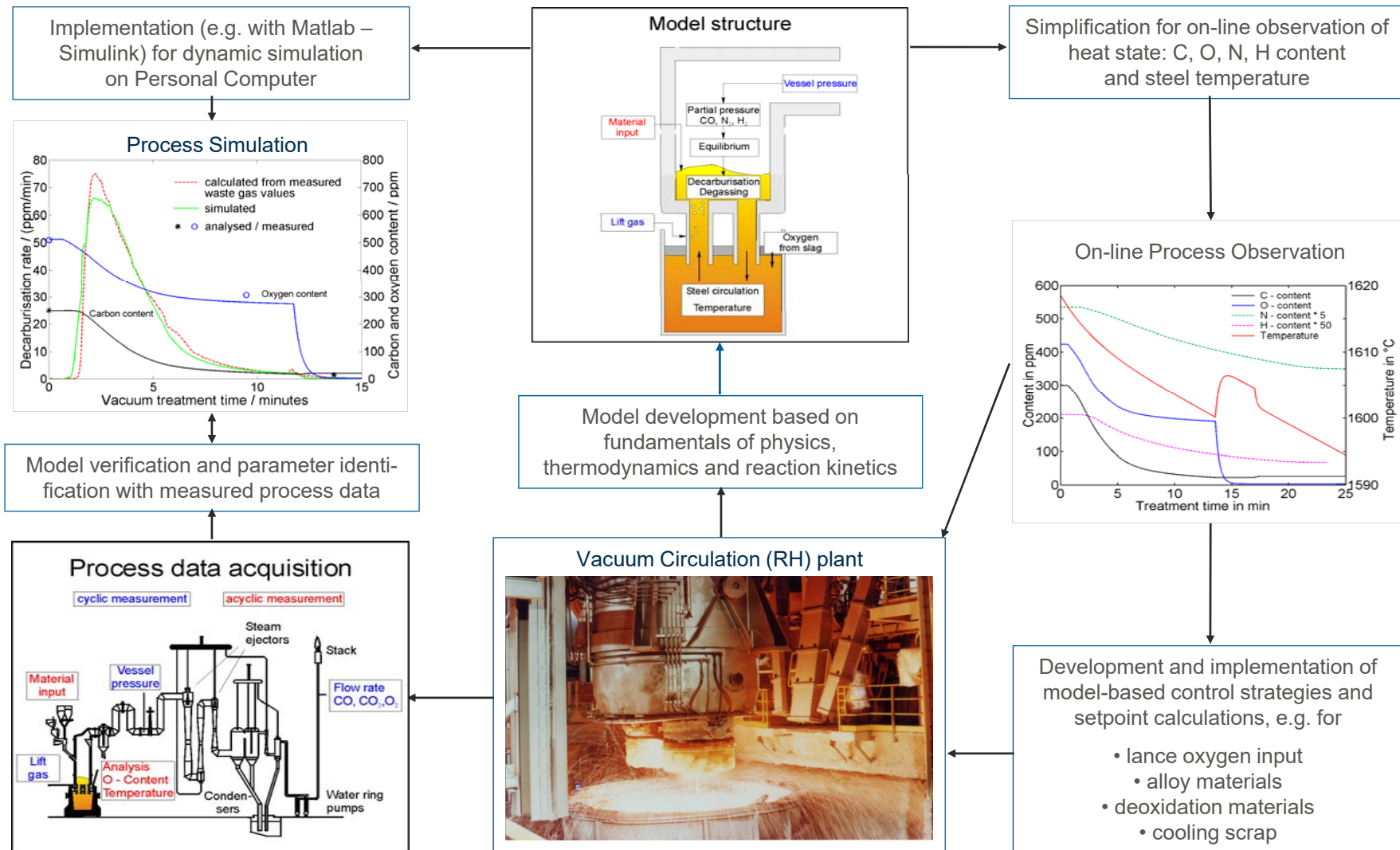 › Implementation of model-based process control within Level-2 (MES) systems

Dynamic process models as basis for on-line control

Dynamic process models

› are based on a cyclic calculation of energy and mass balances

› take into account thermodynamic equilibrium conditions and reaction kinetics for the different metallurgical reactions

› use as inputs

  › cyclically measured process data like process gas flow rates, vessel pressure, off-gas data etc.

  › data of acyclic process events like material additions, steel and slag analyses, steel temperature measurements etc.

On-line applications

› Continuous on-line monitoring of the actual heat status regarding weight, temperature and composition of steel and slag

› Prediction of the further evolution of the heat status, e.g. for end-point control

› Calculation of set-points for process control at single aggregates, e.g.:

  › for electrical and chemical energy input

  › for oxygen supply for decarburisation, dephosphorisation and temperature control

  › for addition of alloy materials, slag formers, cooling, heating and reduction materials

› Through-process modelling, control and multi-criterial optimisation for the complete process route in electric and oxygen steelmaking

# Principles of development and application of dynamic models

Implementation (e.g. with Matlab – Simulink) for dynamic simulation on Personal Computer

Model structure

Simplification for on-line observation of heat state: C, O, N, H content and steel temperature

Process Simulation

On-line Process Observation

Model verification and parameter identi-fication with measured process data

Model development based on fundamentals of physics, thermodynamics and reaction kinetics

Process data acquisition

Vacuum Circulation (RH) plant

Development and implementation of model-based control strategies and setpoint calculations, e.g. for

- lance oxygen input
- alloy materials
- deoxidation materials
- cooling scrap

Process control of vacuum degassing processes (RH, VD)

› Dynamic process models for the RH and the VD degassing process have been developed and applied for on-line monitoring and control in the frame of several ECSC projects which were performed in the time period from 1990 – 2002

› In several RFCS projects the VD process models were combined with innovative measurement techniques (digital imaging, vibration measurement) to improve on-line monitoring, end point control and control of stirring gas flow rate

Dynamic process model for the RH process

Functions of the process model

› On-line observation of decarburisation, denitrogenation, dehydrogenation and steel temperature

› Dynamic prediction of temperature evolution during remaining treatment time

› End point control regarding achievement of target values for T, C, O, H, N

› Dynamic control of oxygen input via top lance for forced decarburisation and chemical heating

› Dynamic control of deoxidation and cooling scrap addition

Required input data

› Vessel pressure and lift gas flow rate (cyclic)

› Start contents of C, O, N, S, (H)

› Start steel temperature

› Steel weight

› Material additions during vacuum treatment

› Optional: Off-gas measurement (flow rate, CO and CO_2 content) to monitor decarburisation behaviour
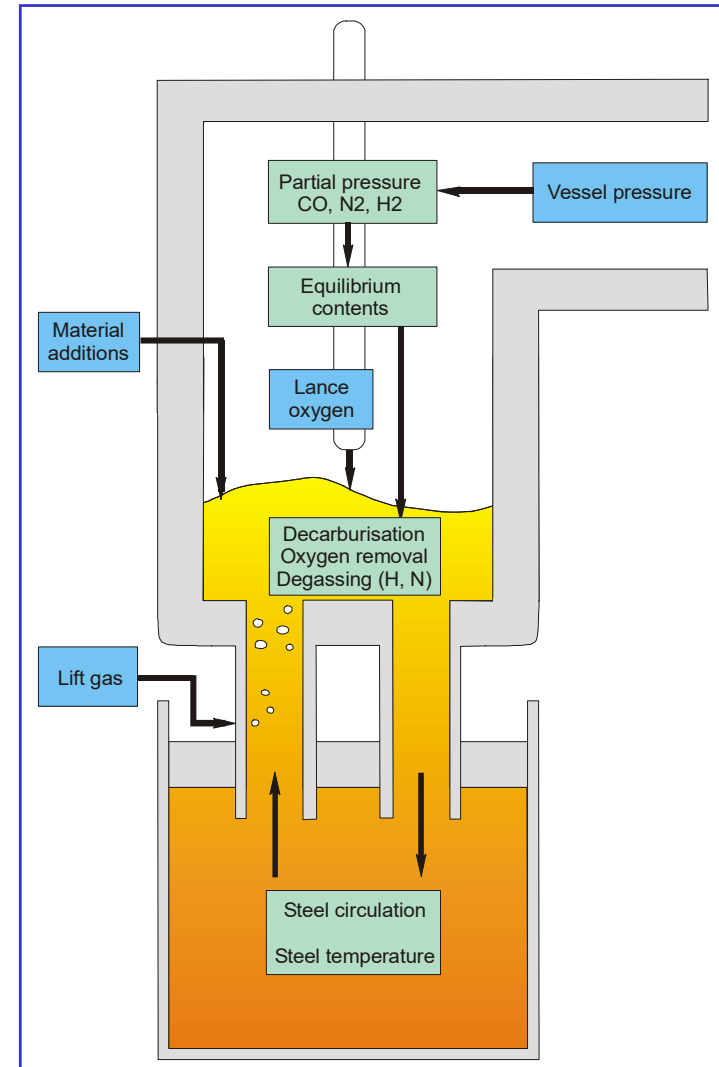
Model-based process control
for RH plants with oxygen top lance

› On-line observation of decarburisation, degassing and melt temperature

› Precise determination of process end point for reduction of process time

› Decreased oxygen consumption for forced decarburisation and chemical heating

› Decreased consumption of deoxidation materials, improved cleanness

› Precise adjustment of target temperature for delivery to the CC plant
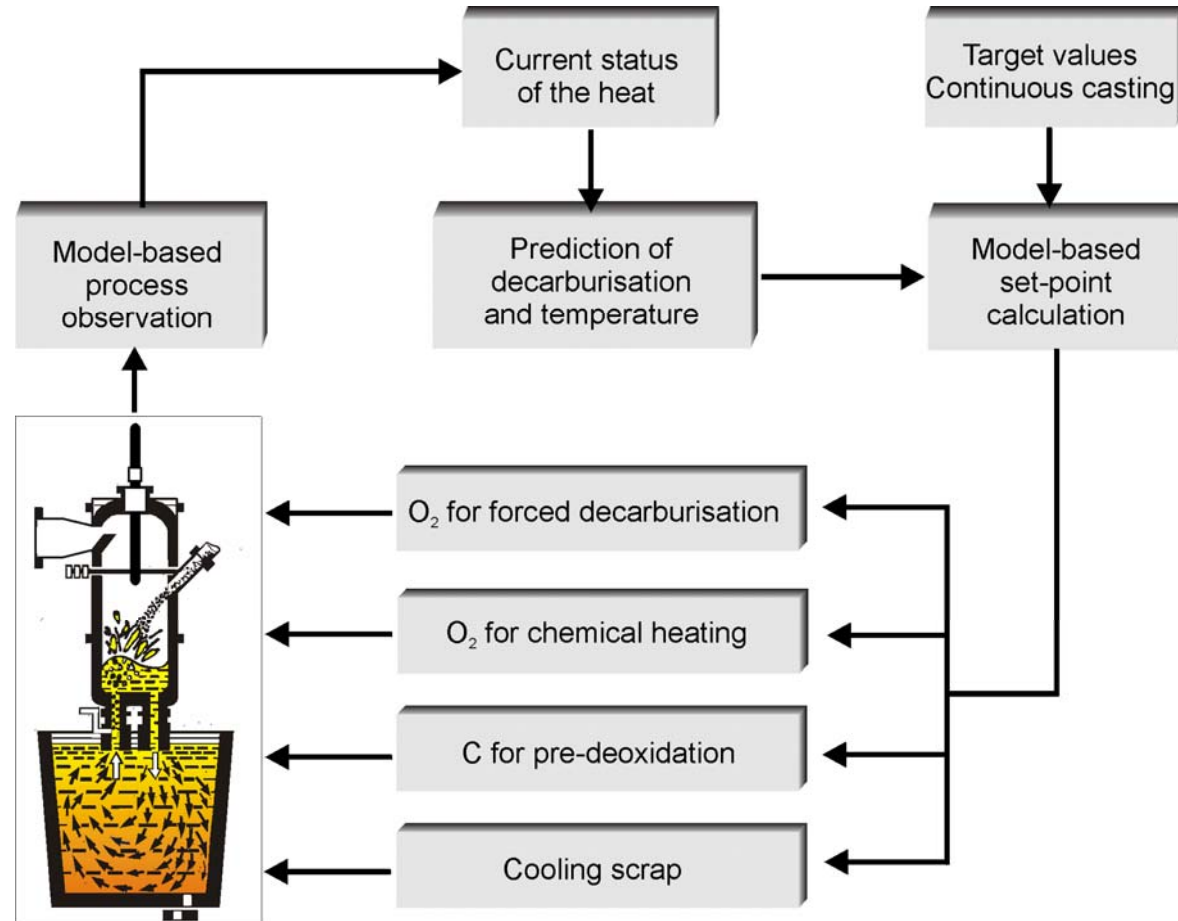
Dynamic model of the Ladle Tank Degassing (VD) process

Functions of the process model

› On-line observation of decarburisation, denitrogenation / nitrogen pick-up, dehydrogenation, desulphurisation and steel temperature

› Dynamic prediction of remaining degassing time and corresponding temperature losses

› End point control regarding achievement of target values for T, C, O, S, H, N

Required input data

› Vessel pressure

› Bottom stirring gas flow rate

› Cooling water flow rate and temperature difference for water-cooled roof

› Heat state at start of treatment

› Weights and types of all charged materials
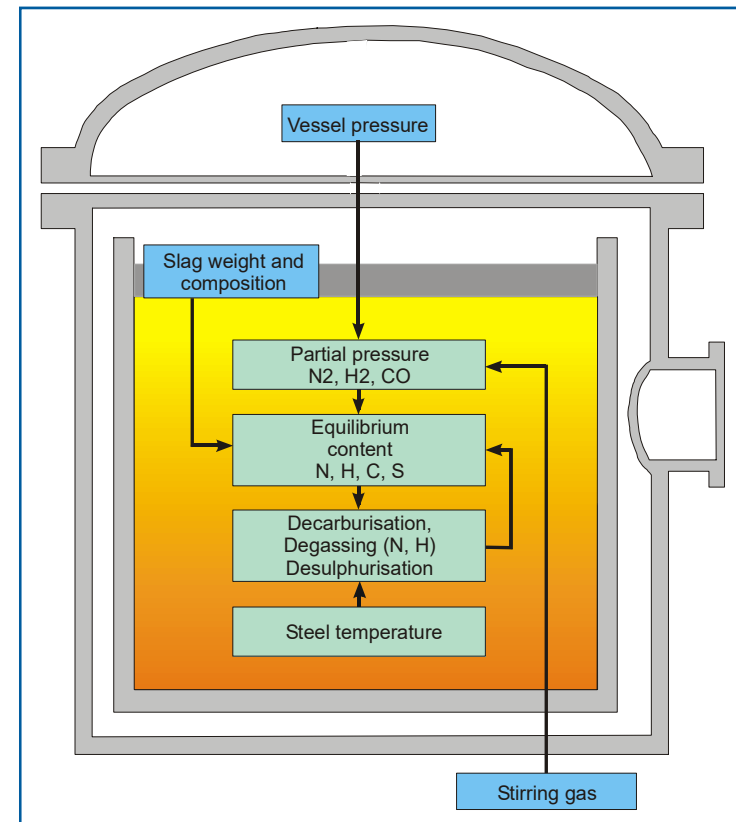
Combination of innovative measuring techniques and dynamic process models for VD process control

› Innovative measuring techniques

- › Infrared imaging
- › State-of-the-art image processing
- ⇨ To determine actual stirring intensity

› Dynamic process model

- › Monitors progress of degassing
- › End point prediction (H, N, C, T, ..)
- › Takes actual stirring intensity in account

→ Optimised process control

- › Minimisation of treatment time
- › Control of stirring gas flow rate
- › Increased process reliability
- › Energy savings
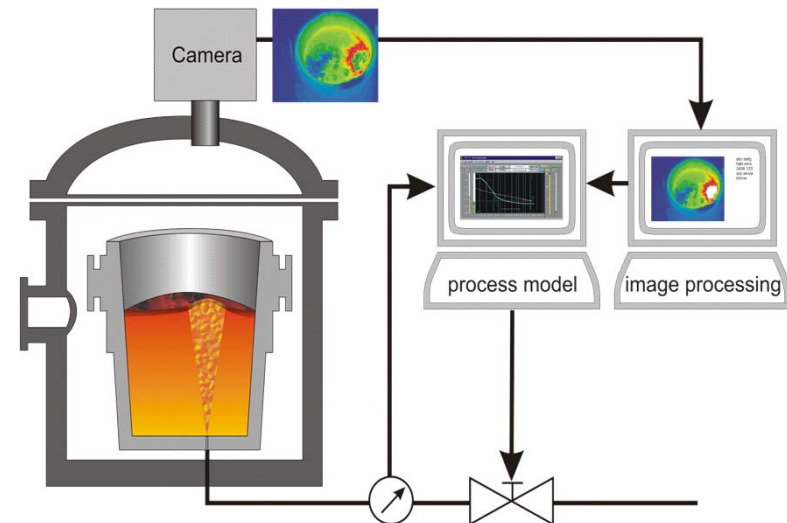
Process control of stainless steel refining (AOD, VOD)

> › Dynamic process models for the AOD and the VOD process have been developed and applied for on-line monitoring and control in the frame of two ECSC and one RFCS project, which were performed in the time period from 1997 – 2010

> › The process models are based on energy, mass and oxygen balances, using in some applications also off-gas data for monitoring of the decarburisation process.
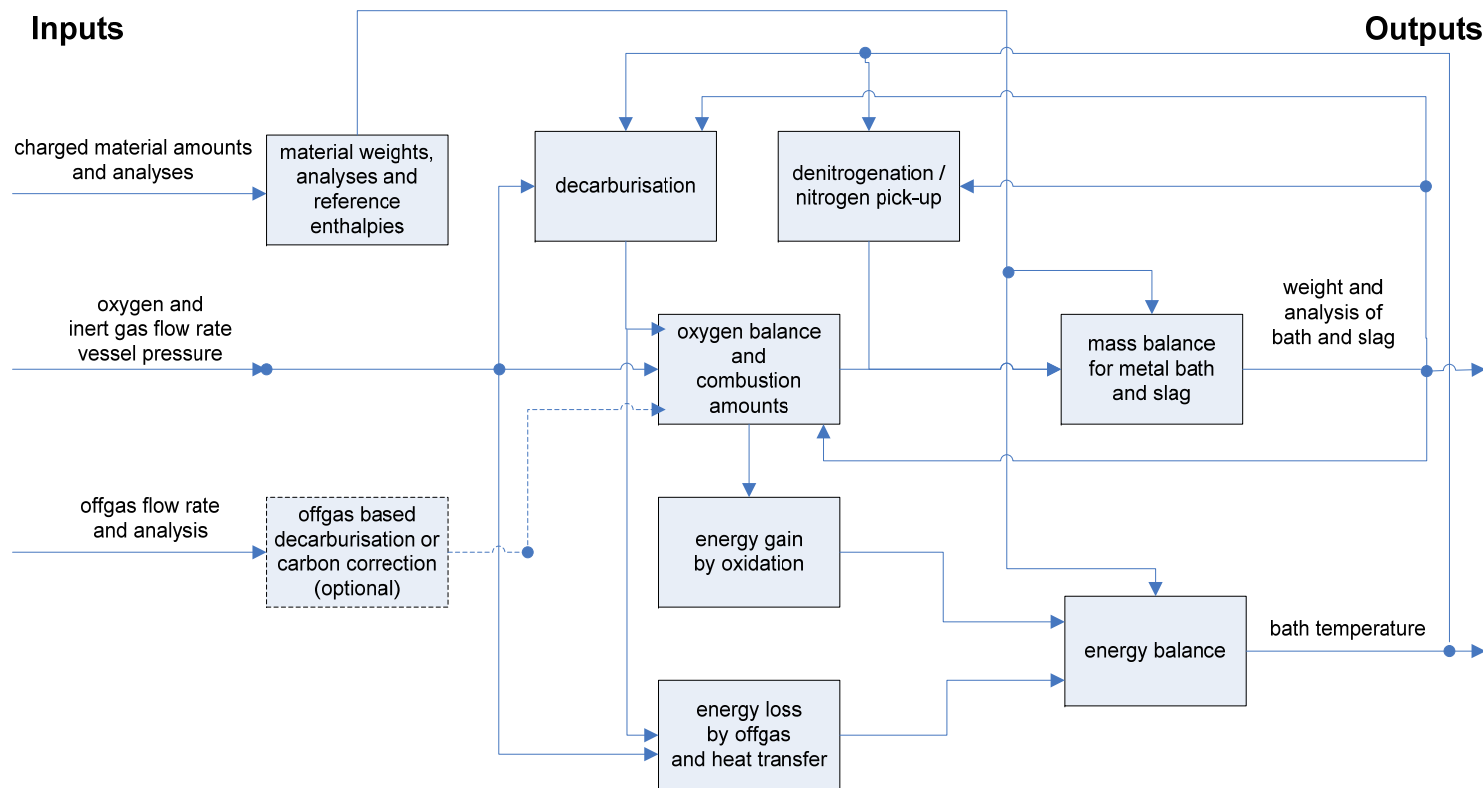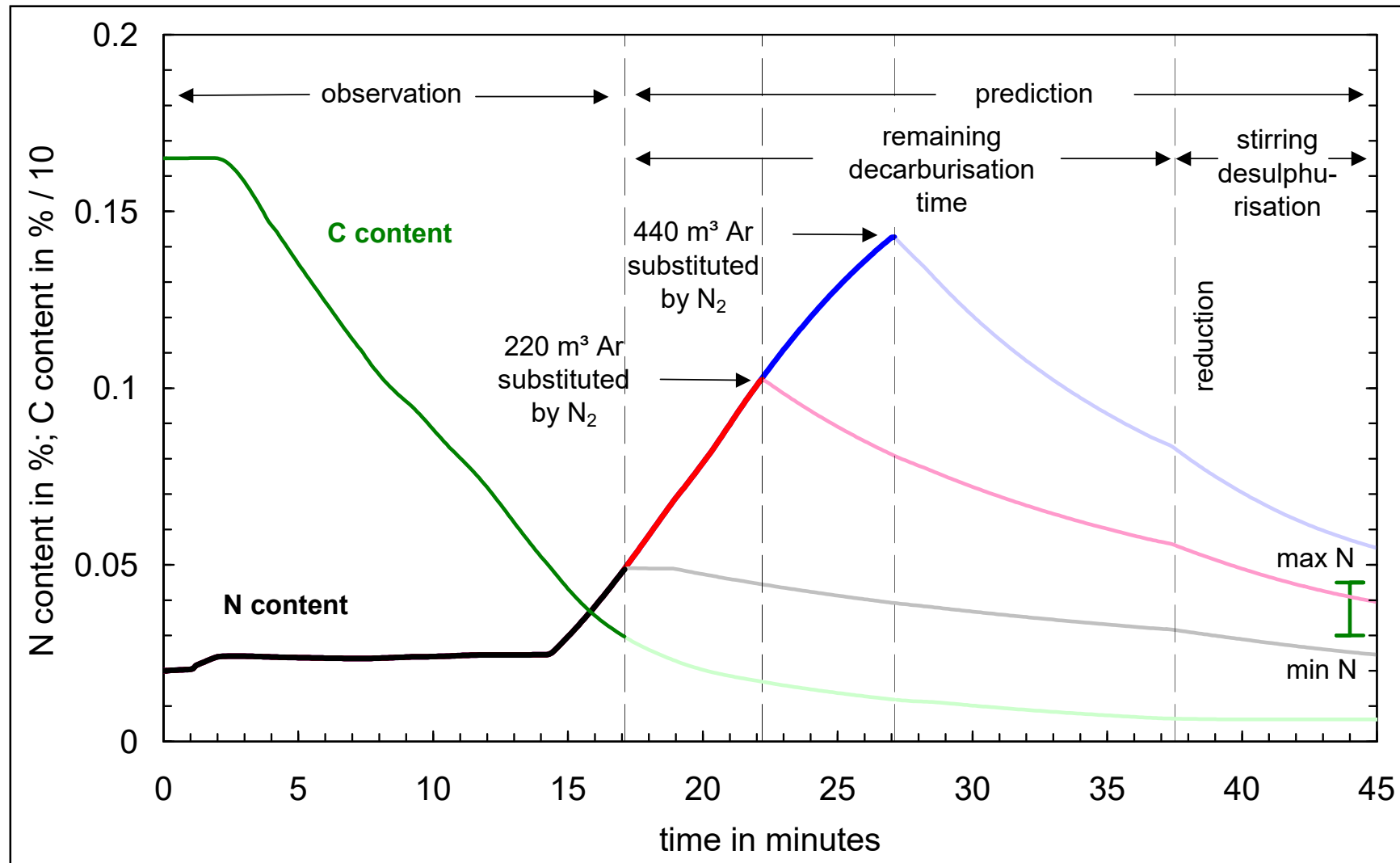
Motivation for dynamic control of oxygen supply:
Oxygen balance for a step-wise controlled heat

Control of oxygen supply depending on the demand for decarburisation and for adjustment of the melt temperature

$\Rightarrow$ Reduced chromium loss

$\Rightarrow$ Decreased consumption of silicon and slag formers for chromium oxide reduction

$\Rightarrow$ Improved accuracy in adjusting the aim melt temperature before reduction
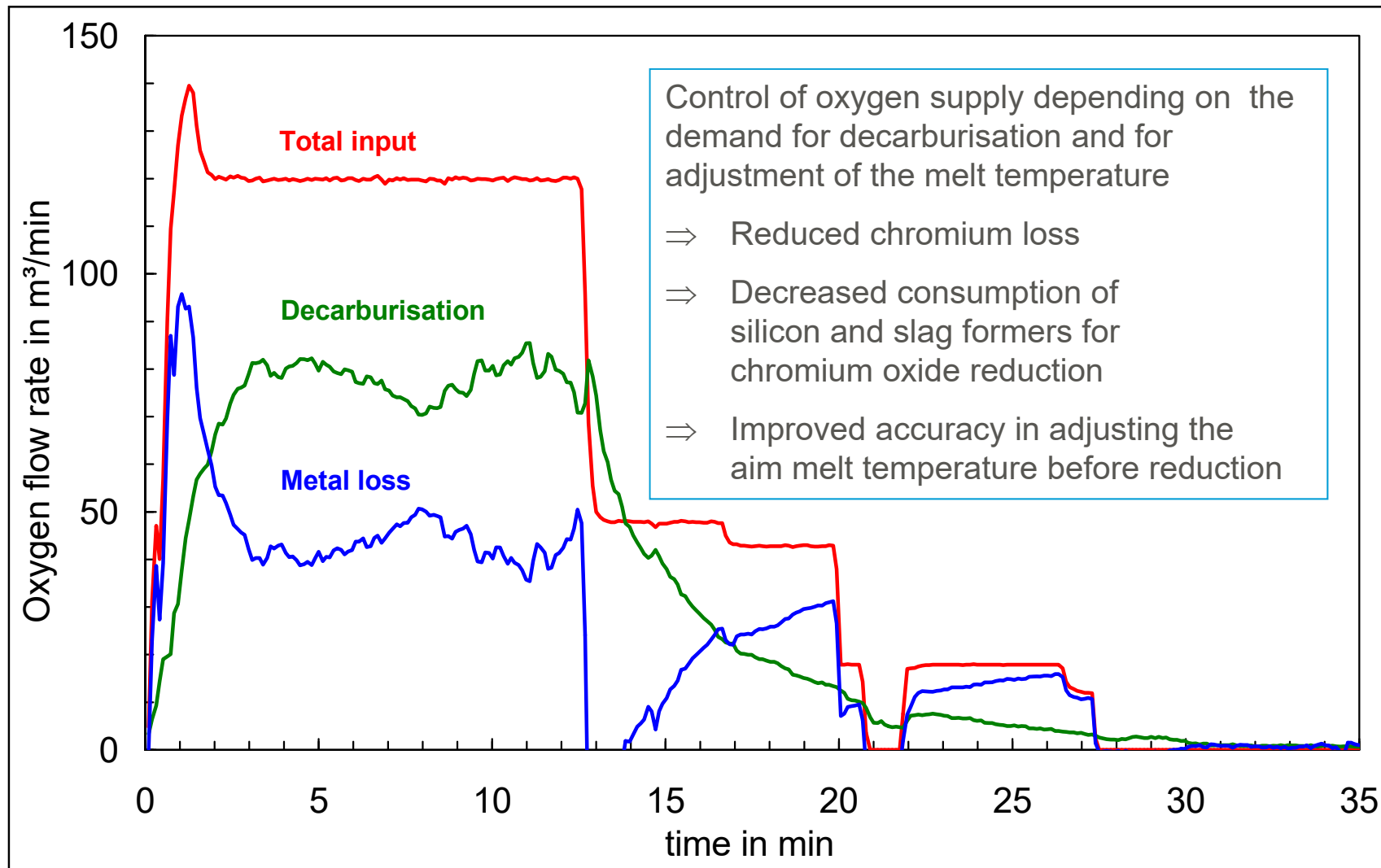
Example AOD heat with dynamic control of oxygen supply
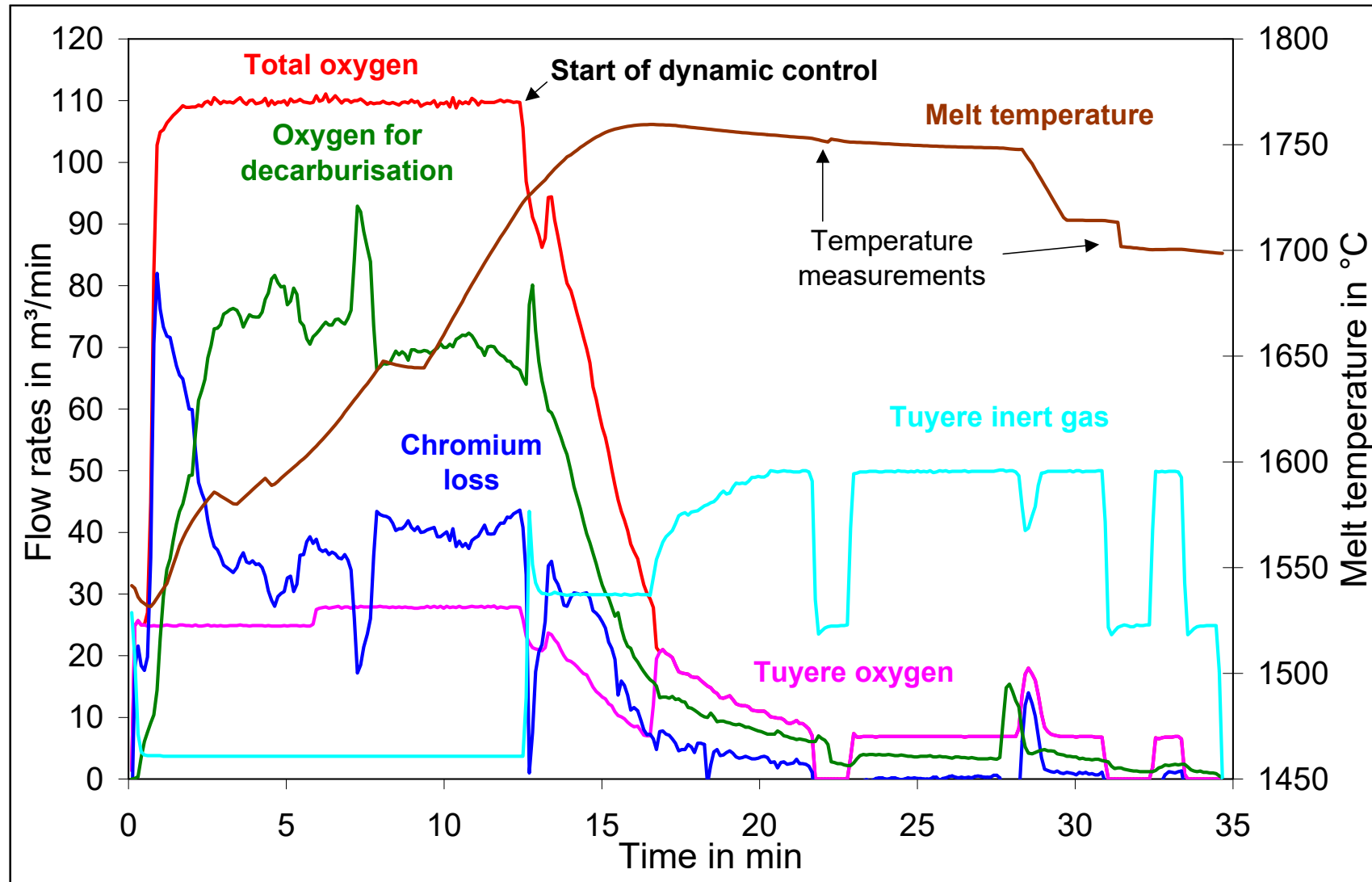
Model-based process control of the VOD plant

Functions of the process model

› On-line observation of decarburisation, chromium loss, denitrogenation / nitrogen pick-up, *dehydrogenation, desulphurisation* and steel temperature

› Dynamic correction of carbon balance based on exhaust gas flow rate and analysis for accurate determination of final carbon content

› Dynamic control of lance oxygen input in the decarburisation phase to minimise the chromium loss

Required input data

› Vessel pressure

› Bottom stirring gas flow rate and type

› Lance oxygen flow rate

› Offgas values for correction of decarburisation rate at critical point

› Weights and types of all charged materials
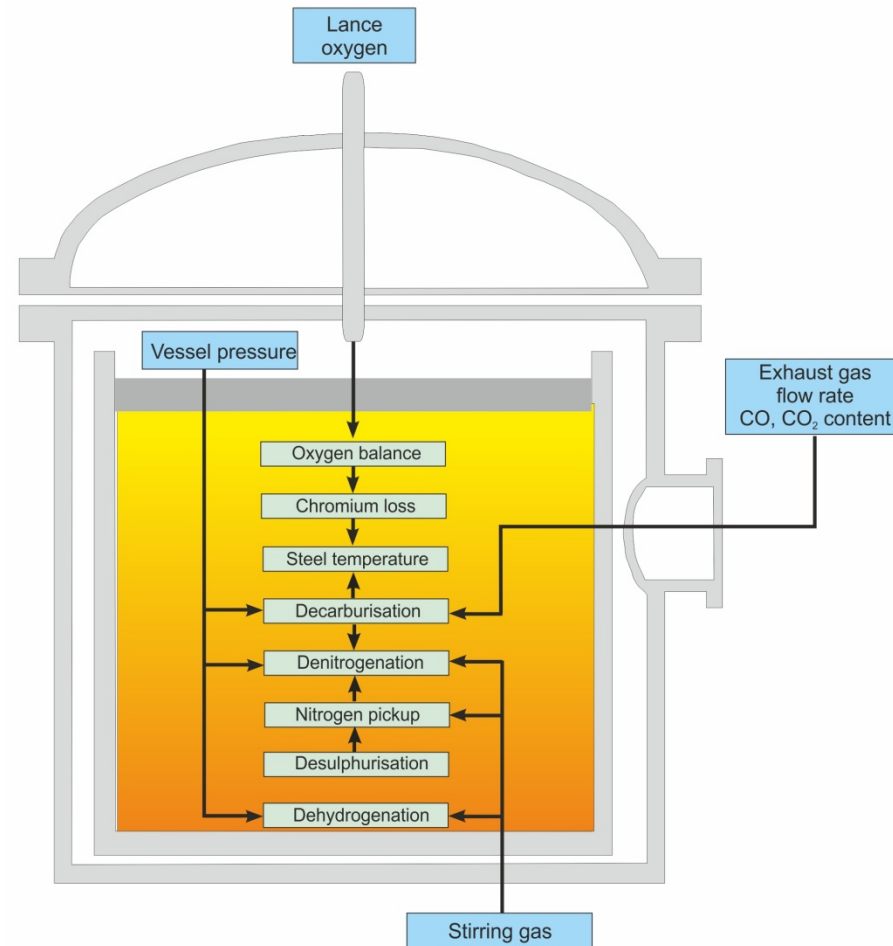
Concept for comprehensive model based dynamic control for stainless steel refining processes (VOD, AOD)

Current status of the heat
- Steel and slag composition
- Steel temperature

Model-based process observation by
- Thermodynamic models for decarburisation and nitrogen removal/pickup
- Dynamic oxygen balance
- Dynamic energy balance

Prediction of
- Decarburisation
- Nitrogen content
- Steel temperature

Vacuum pressure to enhance decarburisation

O_2 for decarburisation

O_2 for chromium combustion to adjust the steel temperature

Optimal switching from N_2 to Ar inert gas to adjust nitrogen content

Dynamic control functions

Through process control of the entire liquid steelmaking route

Objectives

› Development of a through-process control strategy for reliable achievement of target values for delivery of the melt to the casting plant:

  › liquid steel temperature

  › liquid steel quality, especially w.r.t. low carbon, nitrogen, hydrogen and sulphur levels

› Optimisation of the operational practices in terms of energy and material input as well as productivity aspects

Applied methods

› Integration of process models for the single aggregates of the process chain regarding steel temperature, pick-up and removal of carbon, nitrogen, hydrogen and sulphur into a through-process online monitoring and control system for the complete liquid steelmaking route (from scrap yard up to start of casting)

› Combination of integrated model calculations with suitable optimisation tools for optimal layout of treatment practices with regard to quality, costs and productivity

› Dynamic adaption of defined set-points of the treatment practices based on predictive model calculations

So far five RFCS projects performed:

› first project started in 2008, one project is currently ongoing

Through process modelling and control of liquid steel temperature and composition

Integration of dynamic models for

› through-process temperature evolution

› slag balancing and desulphurisation

› vacuum degassing for hydrogen and nitrogen removal

for online monitoring, end-point control and calculation of optimal control set-points
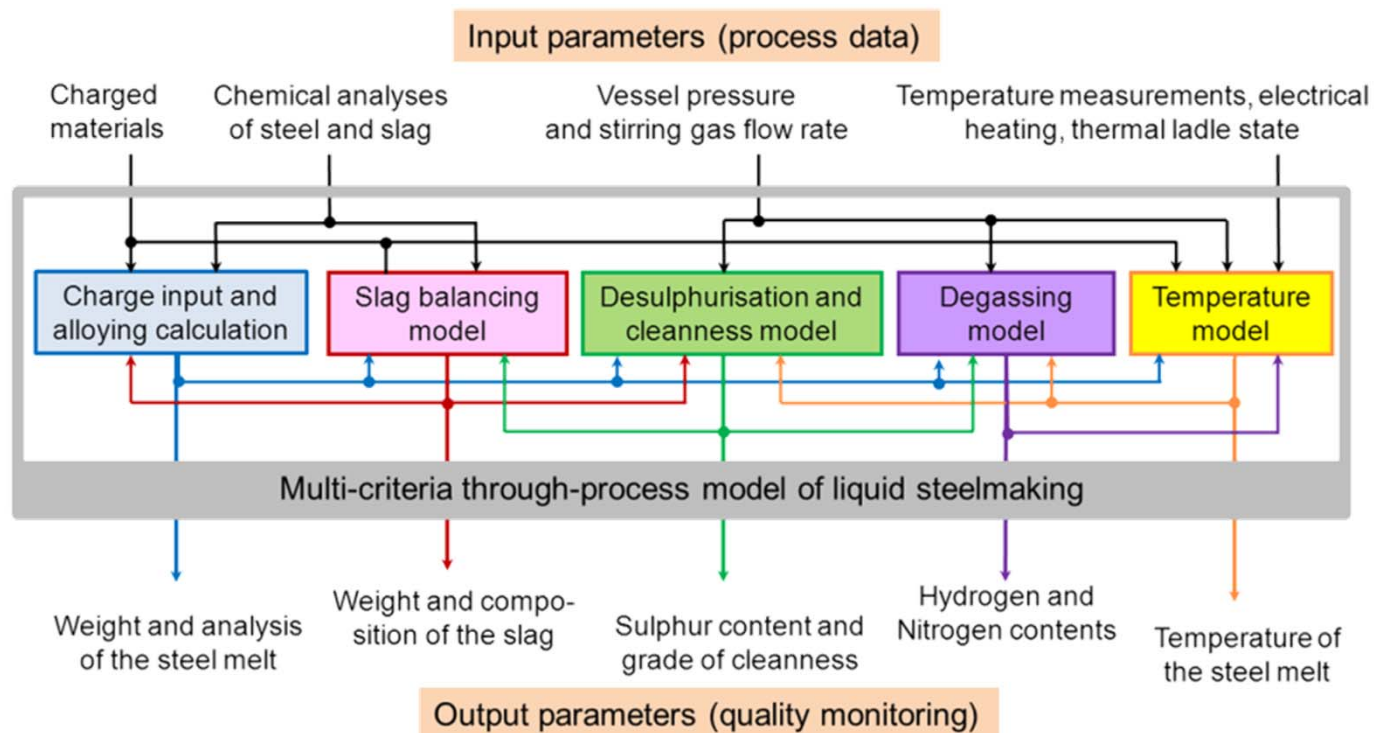
Through process modelling and control of carbon and nitrogen content (LowCNEAF)

Combination of different dynamic process models and regression / statistical models to a through process control approach for the complete electric steelmaking route

› EAF charge material selection with a cost optimal charge input calculation

› Control of decarburisation in the EAF based on a dynamic carbon balance model down to the required C content at tapping

› Selection of alloys by a cost optimal alloy calculation with restriction of C and N pick-up

› Control of denitrogenation during vacuum degassing with monitoring of the achievement of the required Nitrogen end-point via a dynamic degassing model
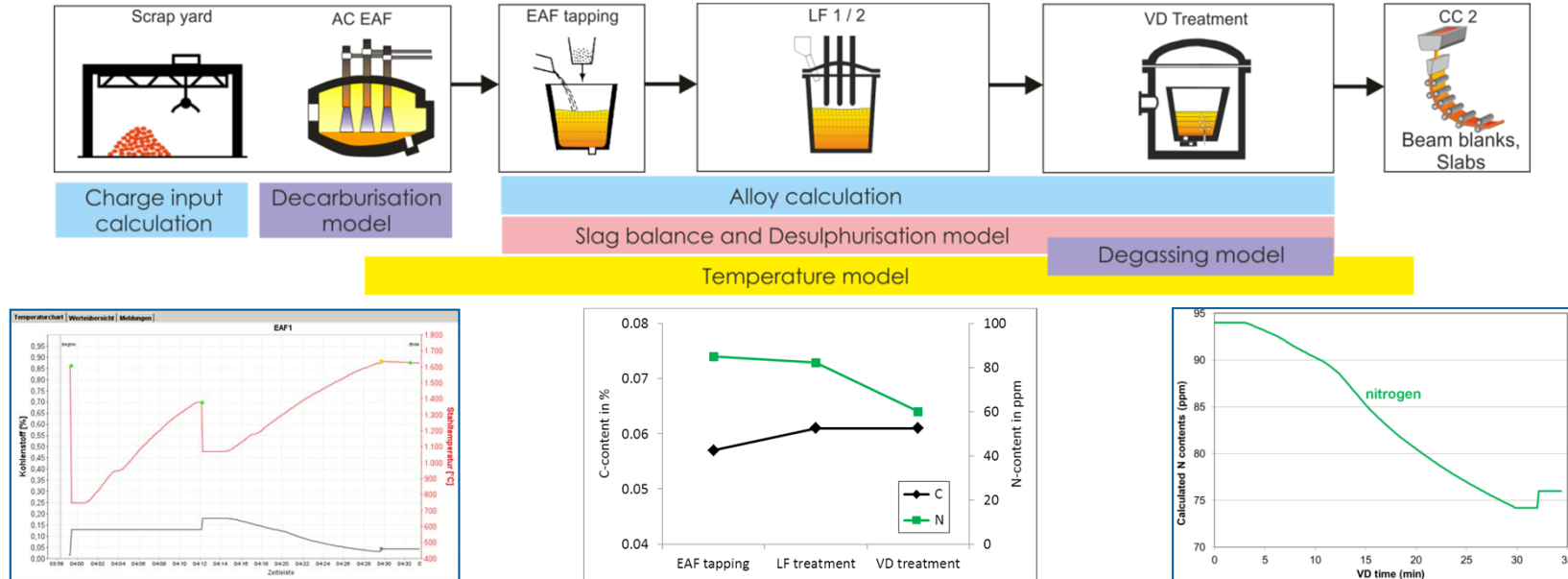
Ladle slag balance model for optimisation of slag former additions (OptDeSlag)
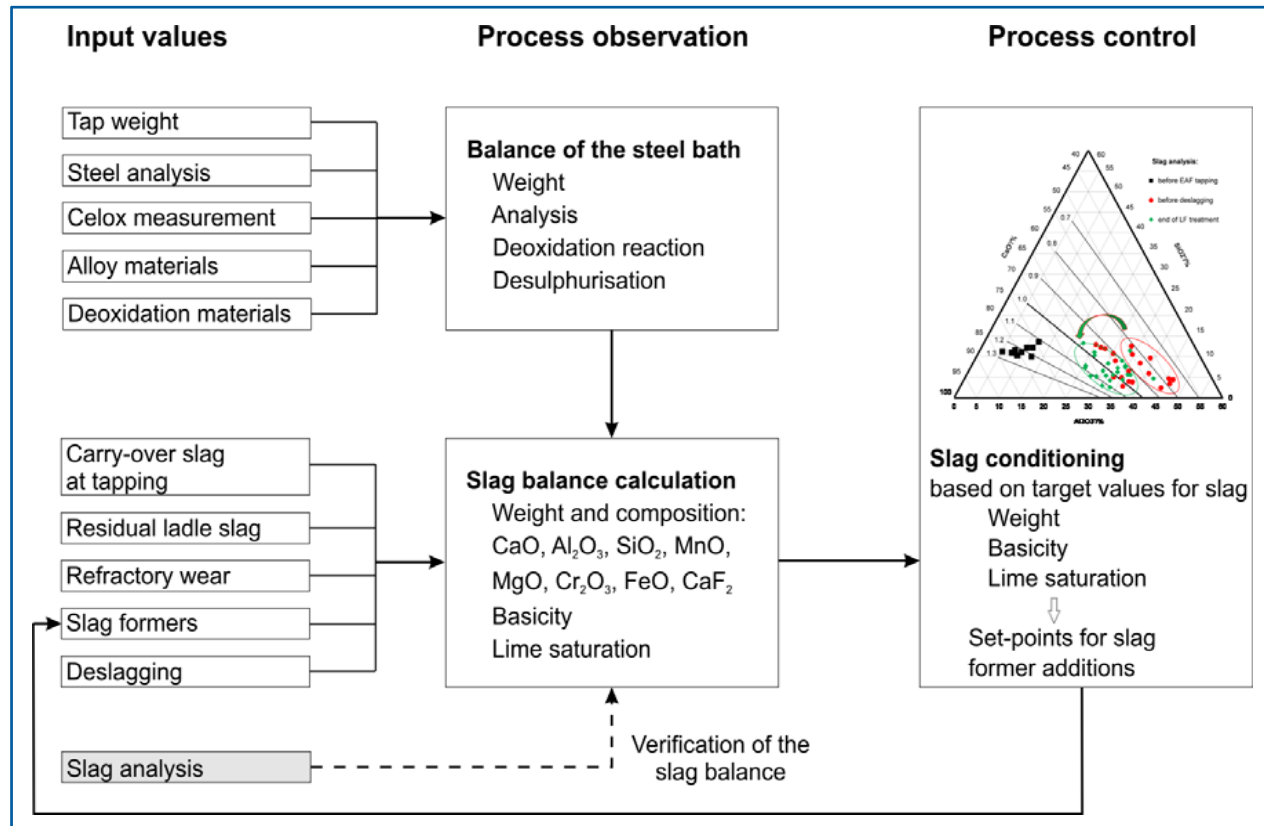
› Model-based balance calculation for on-line monitoring of ladle slag amount and composition

› Determination of amounts of slag former additions for optimal metallurgical operations depending on interaction between steel and slag (desulphurisation, inclusion removal)

# Results of through process slag balance modelling (OptDeSlag)
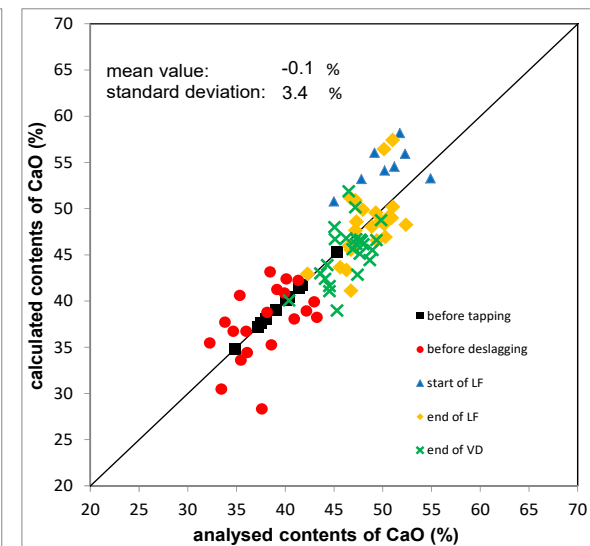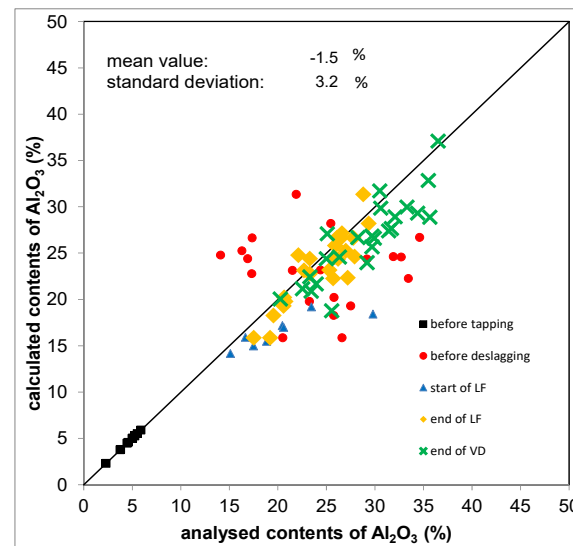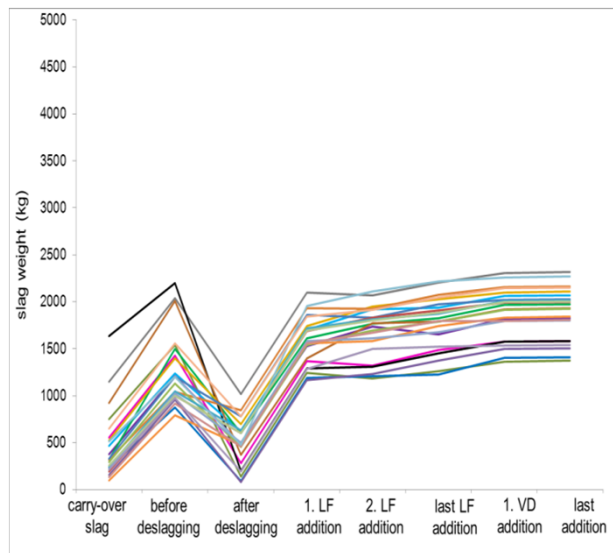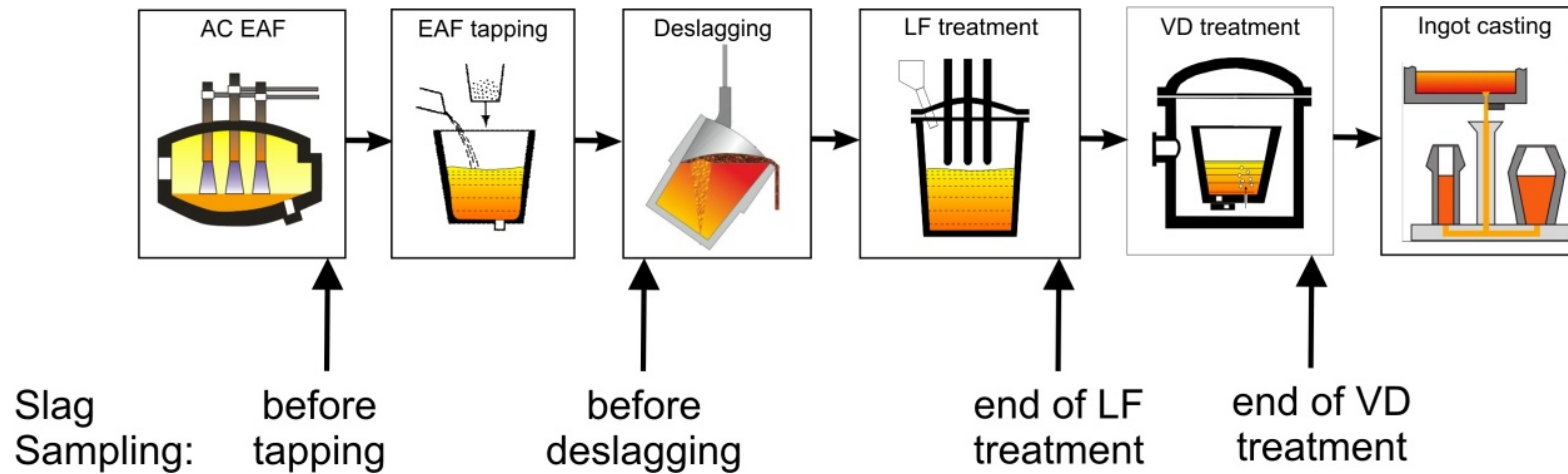
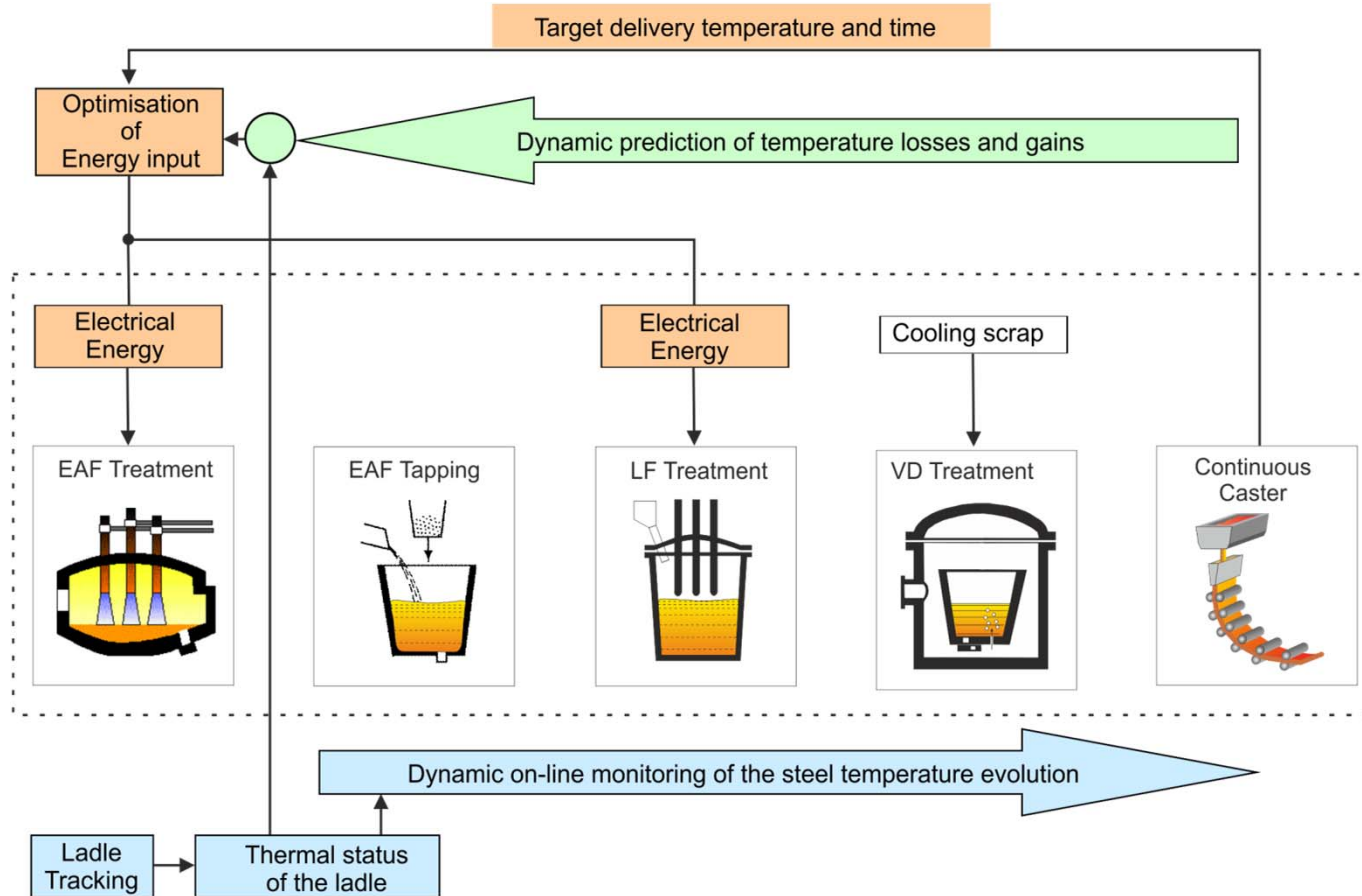# Through process modelling and control of steel cleanness (IntCleanCon)
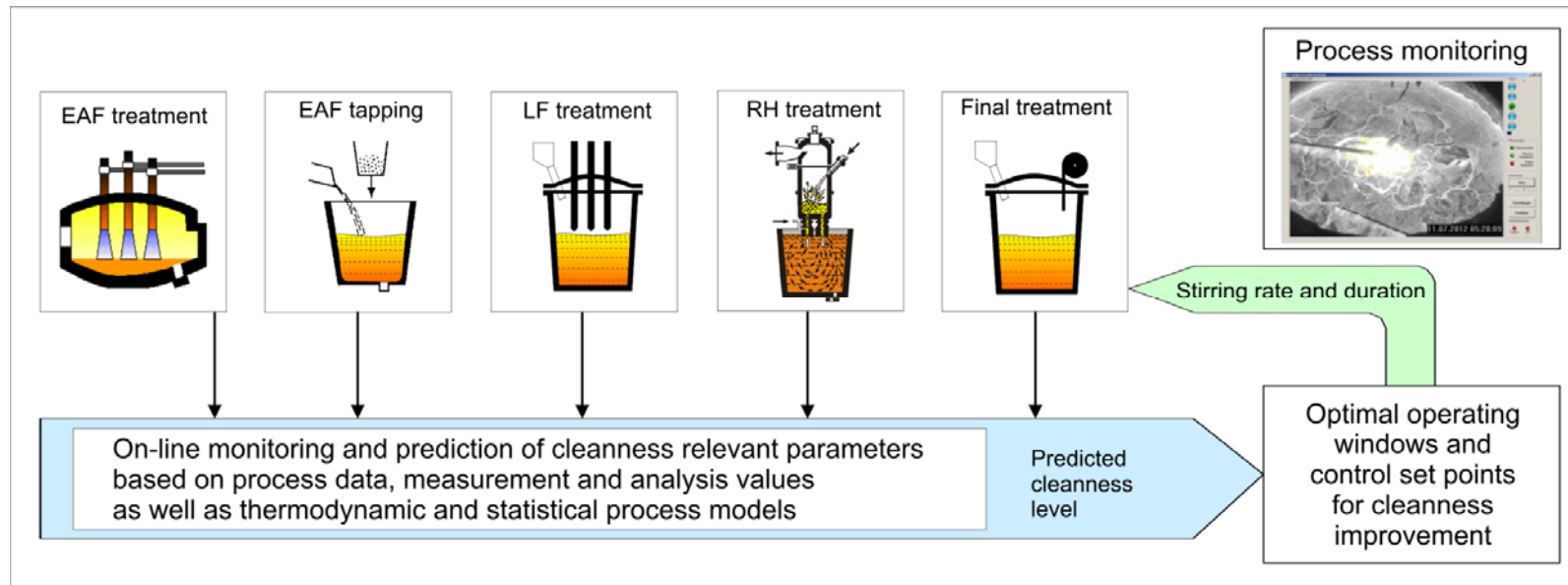
- › On-line prediction of evolution of cleanness index based on through-process monitoring of relevant process parameters (deoxidation, desulphurisation, vacuum and stirring parameters, with focus on prediction of cleanness indicator before start of final stirring treatment

- › Validation with cleanness index derived from inclusion density determined by ultrasonic testing of solid strand samples

- › Determination of optimal stirring pattern (intensity, duration) for final stirring treatment based on predicted level of cleanness

- › Camera-based monitoring and operator guidance for optimal stirring intensity

Dynamic modelling and control of temperature evolution (PlantTemp, TotOptLis)

› The dynamic temperature model considers

  › initial heat state after tapping to be calculated from last steel temperature and analysis in EAF and tapping process with material additions including deoxidation reactions

  › ladle history data (ladle empty time, preheating duration and ladle age) for determination of dynamic temperature loss rate

  › additional temperature losses by inert gas stirring and vacuum treatment

  › cooling effect of alloy material, cooling scrap and slag former additions

  › electrical energy input at LF

  › temperature gain by oxidation reactions
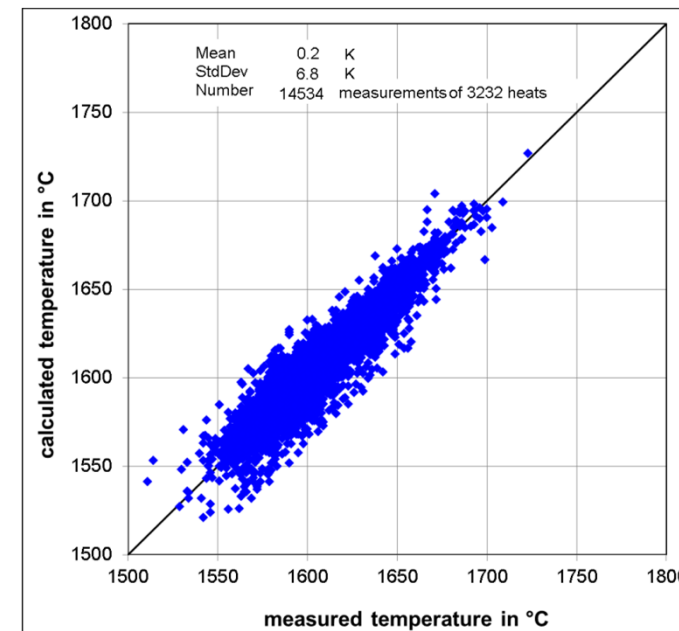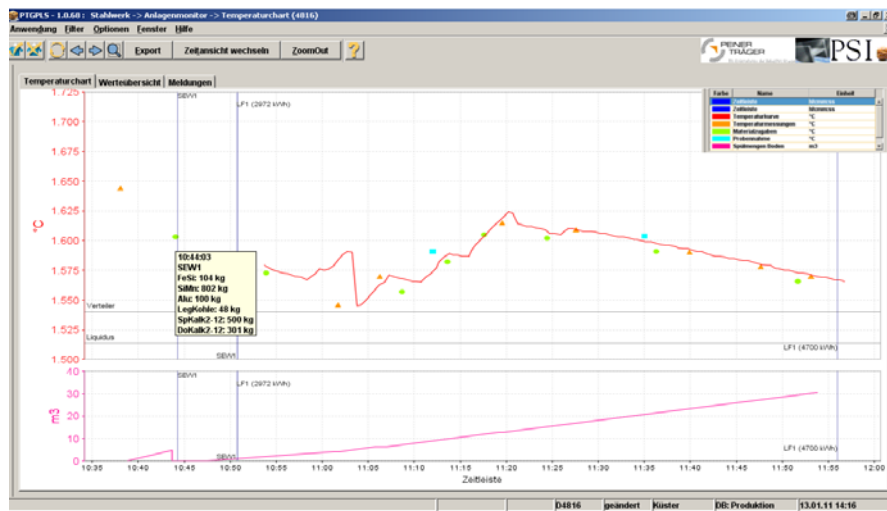
Through process temperature control in electric steelmaking

Target delivery temperature and time

Optimisation of Energy input

Dynamic prediction of temperature losses and gains

Electrical Energy

Electrical Energy

Cooling scrap

EAF Treatment

EAF Tapping

LF Treatment

VD Treatment

Continuous Caster

Dynamic on-line monitoring of the steel temperature evolution

Ladle Tracking

Thermal status of the ladle

› Monitoring and prediction of temperature evolution throughout the ladle treatment

› Consideration of thermal ladle status

› Optimal control for electrical energy input in LF and for EAF tapping temperature

› Increased accuracy in meeting the target casting temperature

› Reduced electrical energy input in LF and EAF

› Avoidance of cooling scrap addition or enhanced stirring for cooling

# Through-process temperature and quality control exemplified for the electric steelmaking route
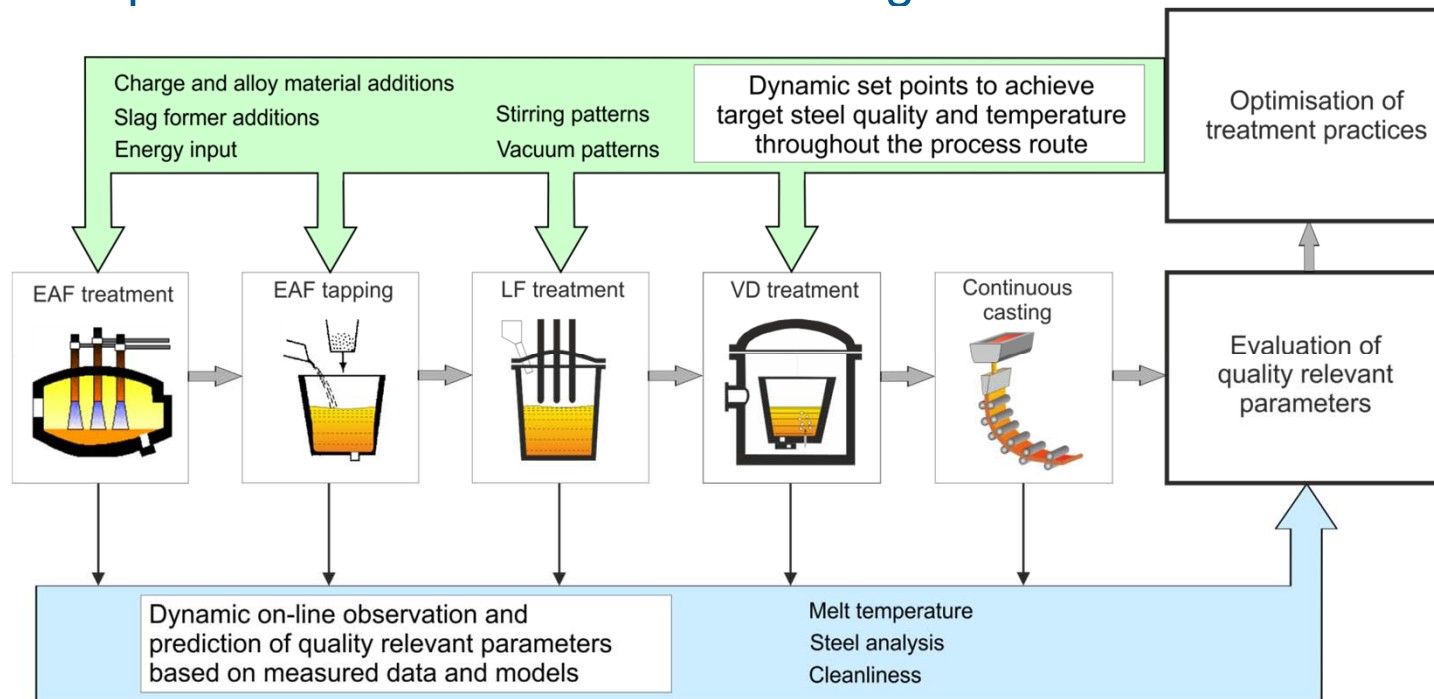
- › Integration of dynamic process models to monitor and control the heat state evolution throughout the complete process route

- › On-line control along the process route by combination of predictive model calculations with optimisation tools for adaption of treatment practices and model-based set-point calculations

- ✎ Temperature and quality targets can be achieved under minimum material, energy and production costs with maximum productivity

- ✎ Improved steel quality, less downgrading due to violation of limits for C, N, H or S targets

Dynamic optimisation of treatment practices (TotOptLis)

› Model based through-process prediction calculations start with actual heat status and use process conditions as defined by practice data for remaining treatment steps

› For variable practice data, optimal set-points are calculated within given limits by iterative applications of prediction functions, using heuristic rules and regula-falsi algorithms to adjust treatment aims with minimal energy and material consumption

› In case of conflicts between different production aims regarding heat delivery time, steel temperature and quality, rules adjust

1. treatment durations according to target heat delivery time

2. target steel quality in terms of H, N, S contents and cleanness requirements

3. target steel temperature

Remaining conflicts are displayed to the operator in order to solve them manually

T (steel temperature)
t (delivery time to CC)
Q (steel quality – chemical analysis & cleanness)
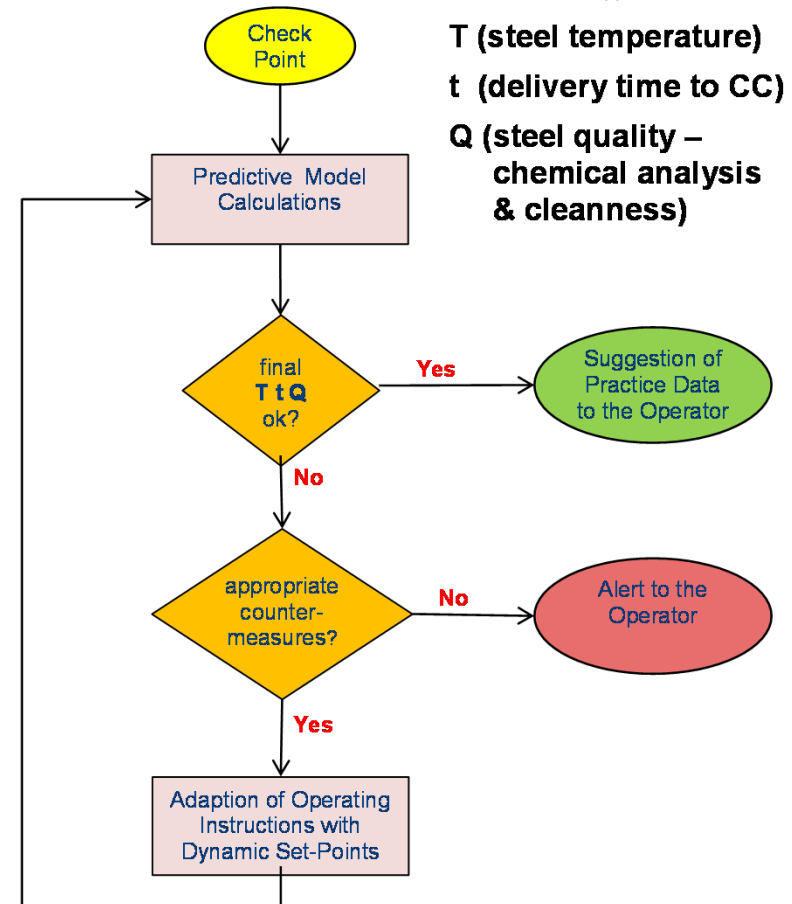
Configuration and monitoring of SecMet treatment steps within a Level-2 system

Monitoring, prediction and control of temperature evolution within a Level-2 system
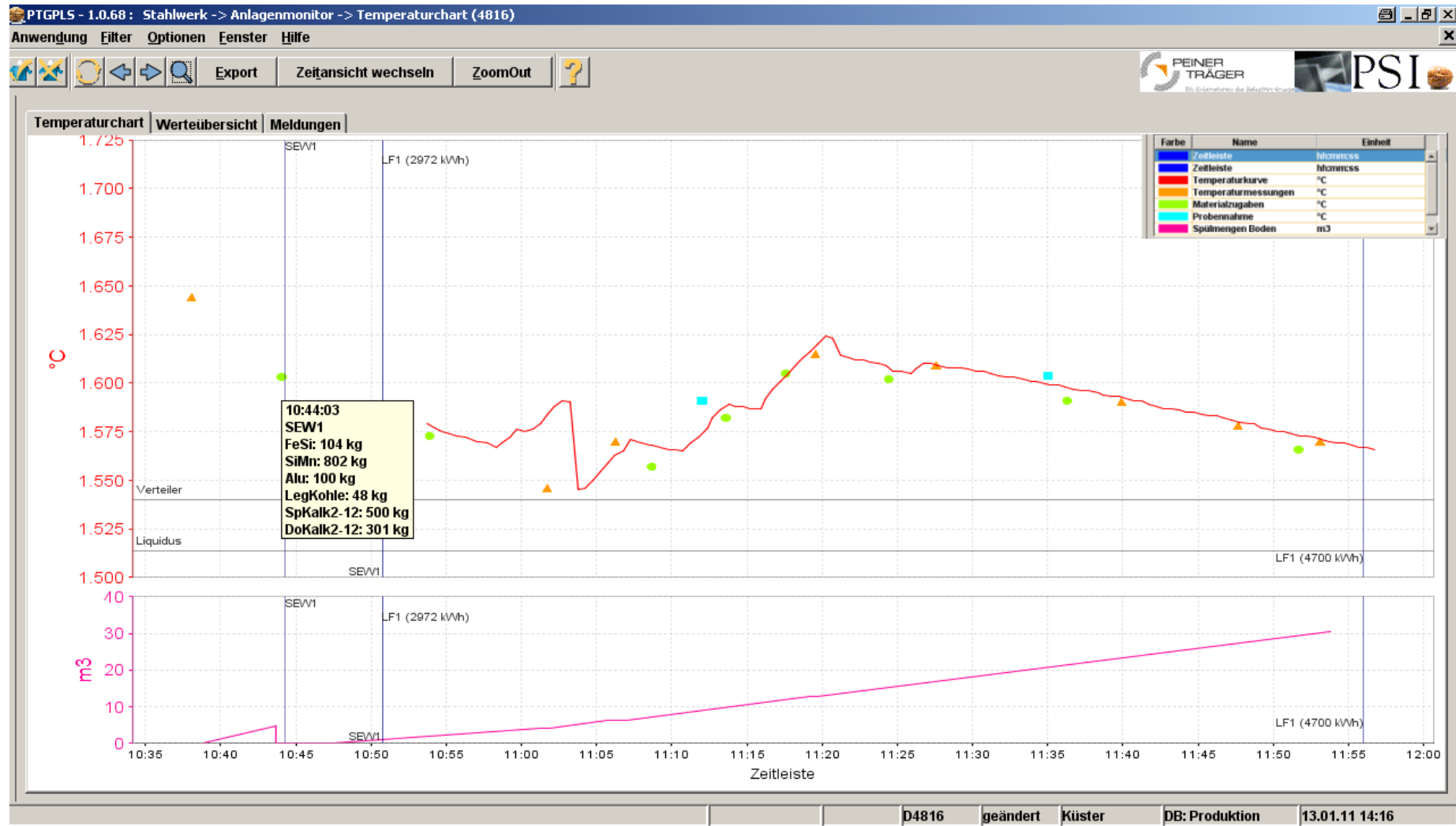
Monitoring, prediction and control of an AOD treatment within a Level-2 system
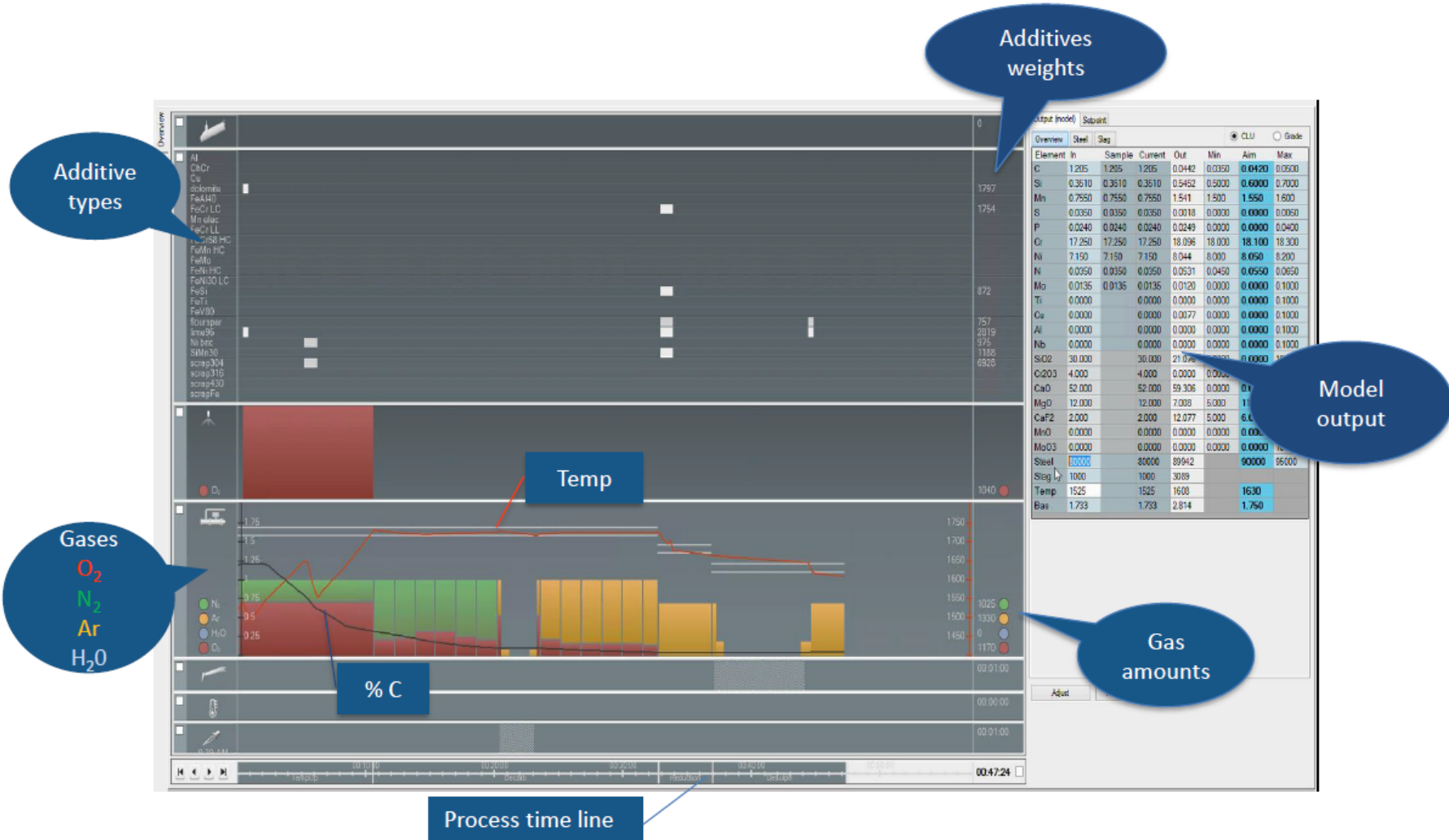
Functions and restrictions of an alloy calculation for SecMet

Input values

› Material composition (scrap analysis , alloy analysis)

› Target analysis of actual production step (e.g. LF) or process step (e.g. fine alloying)

› Target heat weight (mass balance); allow or prohibit dilution if required

Material restrictions

› Weight, analysis, material, material class

   (based on attributes, min-/max-amounts, reliability of analysis, etc.)

› Material availability and accessibility in stock

› Material additions in following treatment steps

› Linear constraints and target key values (e.g. carbon equivalent)

› Yield losses (production lines, material, elements)

Results

› Determines alloy material mix with minimal costs

› Keeps undesired requested elements on a limited level

Summary and conclusions

› Dynamic models for on-line observation provide accurate information on the current melt status regarding temperature and composition

  ↳ Number of temperature, oxygen and hydrogen measurements as well as analysis of steel and slag samples can be reduced

  ↳ Precise end point control, leading to reduced treatment times and less energy consumption

› Dynamic process models allow an accurate prediction of melt status evolution regarding temperature and composition over the entire process route of liquid steelmaking

  ↳ Calculation of set-points for temperature control (oxygen input, cooling scrap)

  ↳ Significant reduction of energy buffer for ladle treatment, leading to lower chemical and electrical energy consumption

  ↳ Improved precision in adjusting the target temperature for continuous casting

  ↳ Control of inert gas supply for nitrogen content and stirring intensity

  ↳ Higher accuracy in meeting quality restrictions regarding steel analysis and cleanness

  ↳ Reduced consumption of alloy, deoxidation and slag former materials

› Today model-based monitoring and control systems are normally implemented within Level-2 process control systems

Future developments and prospects

> Further extension of dynamic process models for secondary metallurgy processes, e.g. with utilisation of thermodynamic data bases (FactSage, Thermocalc etc.)

> Utilisation of further sensor information as input for dynamic model calculations for an extended on-line process monitoring and closed loop control

>> Imaging systems for the bath surface

>> Vibration sensors for stirring and slopping behaviour

>> In-line measurement of liquid melt temperature and composition

> Through process control of the complete process chain of secondary steelmaking becomes more and more important

>> to allow a multi-criterial optimisation of all quality relevant process parameters

>> to consider the interdependencies between the different ladle metallurgy processes

>> Horizontal and vertical integration in the sense of Industry 4.0

Thank you very much for your attention !

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