

## COST 526 – Project S11

Final Report

*Advanced Parameter Optimization Methods Preliminarily Used for Casting Processes*

Project leader:

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### 1. Introduction

COST 526 project S11 focused on design, implementation and application of a model-based optimization environment for casting processes, and the specific process addressed in experimental studies was industrial continuous casting of steel. Continuous casting is used at steel making plants worldwide to produce steel semi-manufactures, such as slabs, billets and blooms. It is a complex metallurgical process in which molten steel is cooled and shaped into semi-manufactures of desired dimensions.

The key components of the steel continuous casting system are the ladle, tundish, mold, and cooling subsystems (see Figure 1). The ladle is used for transporting batches of liquid steel from a steelmaking furnace to the tundish. The tundish holds steel while casting is carried out. It is preheated to enable easier control of the steel temperature. Its most important function is to ensure the continuity of steel flow into the mold. The mold extracts heat from the liquid steel and initiates the formation of a solid shell on the slab moving out of the mold. Heat extraction is performed by coolant (water) flowing through the channels built in the mold. This represents the primary cooling subsystem of the caster. The heat extraction and solidification continue as the slab, led by support rolls, passes through the casting machine. Along the slab, water nozzles are positioned which form the secondary cooling subsystem. Cooling in this region results in complete solidification, and the solidified slab is finally cut into pieces of the ordered lengths.

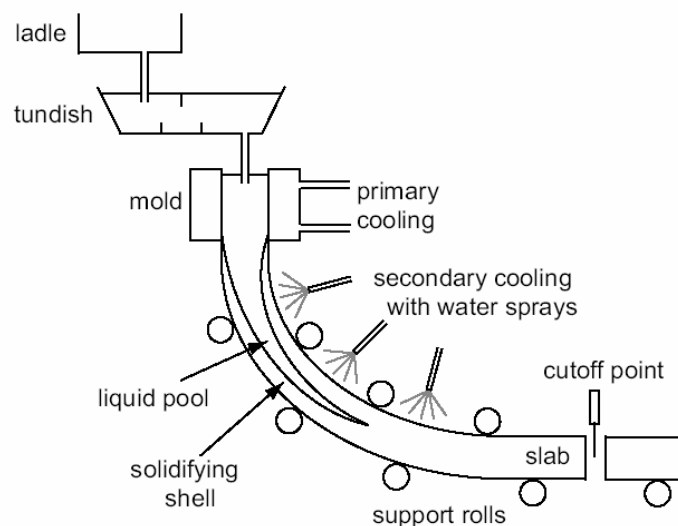


Figure 1: A schematic view of continuous casting of steel

The continuous casting process is subject to various safety, quality, productivity and environmental requirements, but the product quality is among the primary concerns of competing steel producers. The quality of continuously cast steel is determined with respect

to the desired composition and cleanliness of the melt, the required shape and surface smoothness of the products, and the degree of cracking and segregation. The economical relevance of dealing with this process arises from the fact that continuously cast steel represents the major part of the total steel production.

## **2. Goal of the project**

In modern metallurgical practice, the empirical cooling criteria have been introduced to conduct the casting process according to product quality standards. They restrict variations in the slab temperature field to assure the desired product characteristics (Laitinen, 1989). To satisfy these criteria, numerous process parameters need to be properly tuned. Optimizing their values is not trivial as the requirements are often contradicting, and the number of possible parameter settings grows exponentially with the number of parameters involved. Moreover, parameter tuning based on real-world experimentation is not feasible due to the cost and safety risks. Thus a feasible approach to process parameter tuning is numerical optimisation based on a computational model of the casting process.

The primary goal of the project was to implement an optimization system relying on a numerical model of the casting process and capable of optimizing the process parameters with respect to empirical cooling criteria. In addition, during the design phase, a number of optimization-related issues were explored, such as how to design an appropriate quality (cost) function relating the process parameter values with material properties, and which optimization method to use. Finally, the developed optimization environment was aimed at practical application at steel plants.

## **3. Simulator, calibration, quality function and optimization algorithms, including assessment with respect to alternatives**

### **3.1 Simulator and its calibration**

Two versions of the continuous casting process simulator were employed within the developed optimization environment. The majority of work was done using the simulator designed by our national COST 526 partner Nova Gorica Polytechnic. This simulator employs a finite volume method with Crank-Nicolson time discretization and Voller-Swaminathan iteration strategy to compute the temperature distribution in the slab (Šarler, 1996). Using this iterative approach, a temperature field of millions of points is typically calculated. The simulator was calibrated through laboratory measurements of heat transfer coefficient, performed at the Heat Transfer and Fluid Flow Laboratory, Faculty of Mechanical Engineering, Brno University of Technology, Czech Republic, and slab surface temperature measurements at our industrial partner Acroni Steelworks, Jesenice, Slovenia (see Figure 2).

In addition, we performed optimization calculations using the casting simulator developed at the Department of Mathematical Sciences, University of Oulu, Finland. This simulator considers a 3D model of the slab, but takes into account only a quarter of its domain due to the assumed symmetry. The simulator uses the finite element numerical approximation (Laitinen, 2005). Because of its computational efficiency it is capable of on-line process control. It was calibrated through measurements at the Rautaruukki Steel, Finland. A steady-state variant of the simulator was integrated into our optimization environment and tested in off-line parameter optimization.

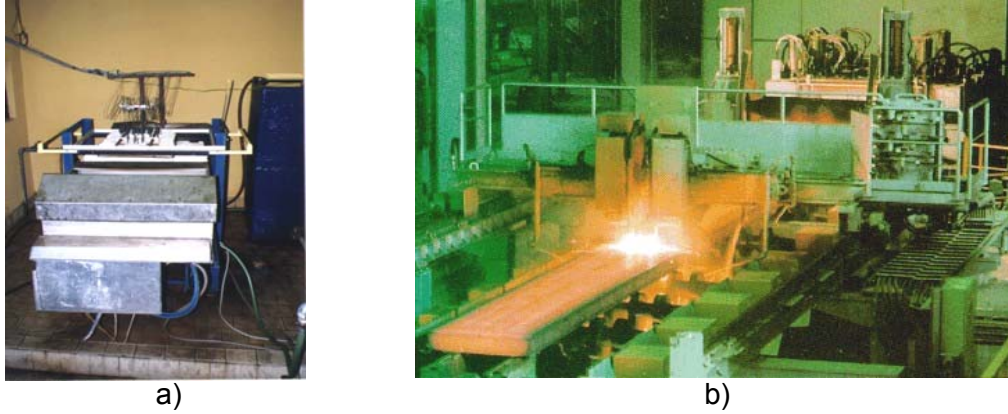


Figure 2: Calibration of the continuous casting process simulator: a) laboratory measurements of heat transfer coefficients, b) slab surface temperature measurements

### 3.2 Quality function

The quality function used with the Acroni continuous casting simulator was defined over the empirical cooling criteria. The following criteria were evaluated after the temperature field calculation:

- maximum depth of the liquid pool,
- maximum slab surface cooling rate in the secondary cooling zone,
- maximum slab surface reheating rate in the secondary cooling zone,
- minimum slab surface temperature in the unbending point,
- maximum negative deviation of the slab surface temperature in the secondary cooling zone, and
- maximum positive deviation of the slab surface temperature deviation in the secondary cooling zone.

Finally, the quality value was obtained as a weighted sum of normalized criteria values  $c_j$ ,  $j = 1, \dots, N_c$ :

$$f = \sum_{j=1}^{N_c} K_j \frac{c_j - c_j^{\min}}{c_j^{\max} - c_j^{\min}}$$

that needs to be minimized. Here  $K_j$  are empirically determined weights denoting the importance of the criteria, and  $c_j^{\min}$  and  $c_j^{\max}$  the lower and upper bounds for the  $j$ -th criterion that are obtained in an initial series of simulator runs. In other words, the optimization task was to minimize the violations of the empirical cooling criteria.

The cost function to be minimized with the Rautaruukki continuous casting simulator was defined as

$$J = \frac{1}{2} \left( \int_{L_M}^{L_Z} (T - T_1)^2 dz + \int_{L_M}^{L_Z} (T - T_2)^2 dz \right)$$

where  $z$  denotes the longitudinal dimension of the slab,  $T_1$  and  $T_2$  are the target centerline and cornerline temperatures, respectively,  $T$  is the actual temperature,  $L_M$  the length of the mold

and  $L_z$  the length of the slab. Hence, the task was to tune the process parameters in such a way that the target temperatures would be approached as closely as possible.

### 3.3 Optimization algorithms

The primary optimization algorithm used is an evolutionary algorithm, implemented in two variants: generational and steady-state. A number of additional algorithms were incorporated into the optimization system for the purpose of performance comparison on various problem instance (Filipič and Robič, 2004; Robič and Filipič, 2004). They include an evolutionary algorithm named differential evolution, the downhill simplex method, also known as the Nelder-Mead optimization method, the conjugate gradient method, and two variants of local optimization: steepest descent and next descent.

The integrated simulator-optimizer environment operates automatically: the selected optimization algorithm navigates the search through the parameter space and invokes the simulator to evaluate the parameter settings, while, given the parameter values, the simulator computes the temperature field in the slab and assesses the metallurgical cooling criteria. The approach complies with the general framework of automatic material process optimization promoted and studied in COST 526.

## 4. Main scientific outcome

The main scientific outcome of the project is a contribution to the methodology of material process optimization which reflects in:

- successful realization of a tripartite approach consisting of a numerical simulator, optimization algorithm and quality function,
- design of quality functions for different tasks in process parameter optimization in continuous casting of steel,
- comparative studies of optimization techniques on selected optimization problems, indicating the most efficient technique for each problem type (see the example shown in Figure 3),
- dissemination of the findings and results through joint working group meetings and publications.

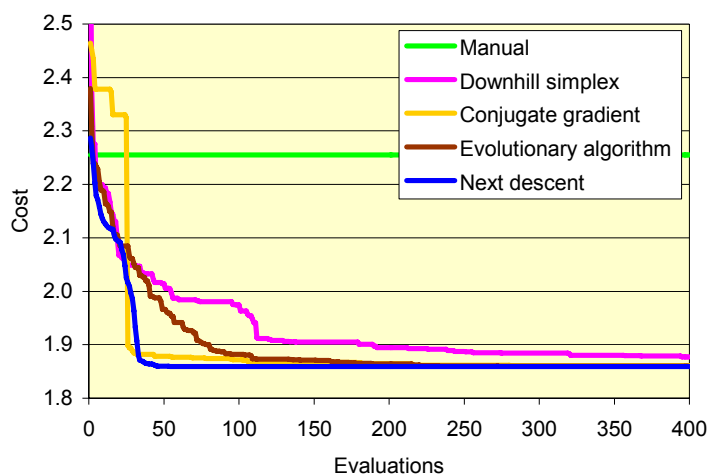


Figure 3: Comparison of optimization algorithms on optimizing 12 secondary coolant flows for steel AC0113 cast at the Acroni Steelworks

## 5. Main technical outcome

The main technical outcome of the project is an implementation of the simulation-based numerical optimization procedure for material process optimization. It has been specifically tested on optimizing industrial continuous casting of steel where practical problems involved of up to 18 process parameters and up to 6 metallurgical criteria. The time performance of the developed software is acceptable for practical use, and the optimized parameters settings, such as the example in Figure 4, have been confirmed beneficial for the process in terms of producing steel semi-products with less defects.

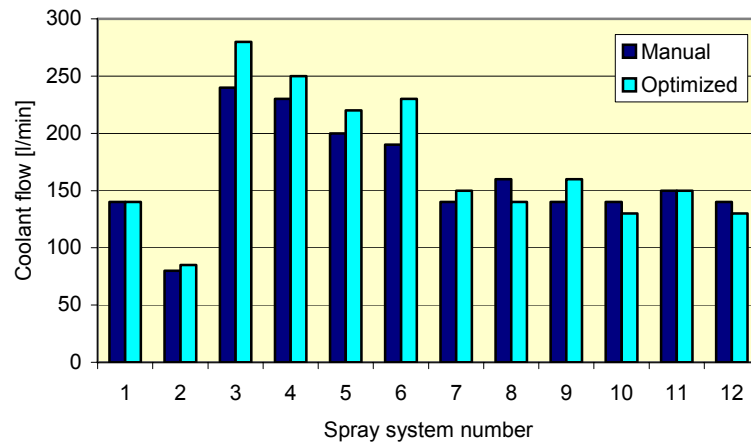


Figure 4: Optimized coolant flow values for continuous casting of steel AC0113 compared with manual settings

## 6. Collaboration within COST 526

National partners:

- Jožef Stefan Institute, Ljubljana (Bogdan Filipič, Tea Robič): optimization algorithms, quality function design, integration with process simulators, comparative studies of optimization algorithms
- Laboratory for Multiphase Processes, Nova Gorica Polytechnic (Božidar Šarler, Robert Vertnik): development and evaluation of a process simulator, quality function design
- Acroni Steelworks, Jesenice (Emil Šubelj): quality function design, definition of optimization tasks, evaluation of results

International partners:

- Department of Mathematical Sciences, University of Oulu, Finland (Erkki Laitinen): an alternative simulator of industrial continuous casting, quality function design, comparative studies on industrial test cases
- Department of Computer Science, University of Aarhus, Denmark (Thiemo Krink, Rasmus Ursem): development and testing of stochastic optimization methods for engineering applications with focus on dynamic optimization problems and noisy cost functions

- Heat Transfer and Fluid Flow Laboratory, Faculty of Mechanical Engineering, Brno University of Technology, Czech Republic (Miroslav Raudensky, Jaroslav Horsky): measurements of heat transfer coefficients to calibrate the numerical model of the steel casting process

## 7. Cooperation with industry

Optimization of process parameters to improve the quality of continuously cast of steel was performed for various steel grades for two industrial partners: Acroni Steelworks, Jesenice, Slovenia, and Rautaruukki Steel, Finland. For the Acroni Steelworks optimization of secondary coolant flows were performed for various steel grades, the optimized settings tested and proven beneficial, while parameter optimization for the Rautaruukki Steel is at a preliminary stage and will be upgraded through further collaboration with Finnish partners.

## 8. References

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