

# Modeling of steel continuous casting: overview of European knowledge and its global standing

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Advancements in modelling are transforming the metallurgy sector, providing more precise tools for quality control and process optimization. In this context, within the framework of an EU-financed dissemination project (METACAST, Research Fund for Coal and Steel), a comprehensive review of solidification modelling in continuous casting and of the research landscape in Europe and worldwide has been performed.

Modelling steel continuous casting and solidification is essential for the accurate optimization of process parameters, such as casting speed and secondary cooling, in order to minimize defects like cracks and segregation. The use of advanced numerical simulations allows the prediction of dendritic structures and improves the quality of the final product. The research examines the fundamentals of thermodynamics, solidification kinetics, and fluid dynamics, and highlights the interplay among heat flow, mass transfer, and thermal stresses, showing their relevance in predicting microstructure formation and defect control. Techniques such as numerical simulation and thermal analysis are used to predict the formation of porosity and shrinkage, thereby improving the quality of the final product. The integration of advanced technologies, such as artificial intelligence and machine learning, is opening new frontiers in solidification modelling, allowing for greater precision and adaptability of models to various production processes.

The scope of the work was to map solidification models and research groups present in Europe by gathering statistical data on their countries of origin and on the areas of interest of the developed models, and to identify common lines between them and compare EU expertise within the global context.

**KEYWORDS:** STEEL SOLIDIFICATION, FLOW, MODELLING, SKILL MAPPING, PROCESS CONTROL;

## FOREWORD

The numerical modelling of steel casting and solidification has become an essential discipline in modern metallurgical engineering, enabling the prediction of process behavior, optimization of industrial operations, and prevention of defects that impact steel quality. Over the past decades, increasingly sophisticated computational approaches have been introduced, allowing researchers and engineers to simulate heat transfer, fluid flow, microstructure evolution, and defect formation with unprecedented accuracy.

Today, numerical models serve not only as design and diagnostic tools but as integral components of digital ecosystems that connect simulations with real casting oper-

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ations through advanced sensors, real-time monitoring, and data-driven optimization. In this evolving landscape, the competencies of research institutions, industrial laboratories, and technology providers play a crucial role, as they shape the development and adoption of innovative modelling techniques across different regions.

The following section provides an overview of the fundamental physical phenomena involved in steel casting modelling, alongside the main numerical approaches used in research and industry. Subsequently, a geographic mapping of leading expertise is presented, highlighting centers of excellence and the regional distribution of modelling capabilities worldwide.

### **CASTING MODELLING SCENARIO**

Numerical methods for modelling steel casting and solidification include the Finite Element Method (FEM), Finite Volume Method (FVM), Cellular Automata (CA) and Phase Field Models (PFM).

The key phenomena in steel casting modelling can be listed as follows.

- Heat Transfer, governing the solidification rate and significantly influencing the grain structure.
- Fluid Flow, affecting heat transfer, solute distribution, and inclusion behavior, via key mechanisms as natural and forced convection (e.g., due to electromagnetic stirring) and buoyancy-driven flow, which influence the flotation of non-metallic inclusions. CFD models are extensively used to study the impact of turbulent flow on solidification and simulate mold flow dynamics, including turbulence and electromagnetic effects.
- Solidification, determining the internal structure of steel (e.g., columnar or equiaxed grains). Accurate modelling requires coupling thermal and fluid flow models, often incorporating Darcy's law, to describe the flow in the mushy zone.
- Solute Redistribution and Microsegregation, affecting the mechanical and chemical properties of the final product and requiring careful modelling approaches to ensure quality control.
- Precipitates, Inclusions and Defect Formation, linked to product quality and object of problem solving.

The development and adoption of commercial and open-source computational tools have significantly advanced the modelling of steel casting processes. These tools implement momentum, heat, and solute conservation equations in user-friendly interfaces. Recent innovations in steel casting and solidification modelling include advanced computational techniques (e.g., multi-physics simulations and high-performance computing), as well as machine learning (ML) and artificial intelligence (AI), which are increasingly being used to predict casting defects, optimize process parameters, and analyze large datasets from simulations and experiments. Real-time monitoring through digital twins, acting as virtual replicas of casting processes, enables online process supervision and optimization.

To substantiate the regional classification, criteria were taken by assuming quantitative indicators from peer-reviewed technical literature and reproducible bibliometrics (Scopus/Web of Science, 2011–2025). Indicators include scientific output, institutional presence, industrial competence (plant-validated modelling/digital twins), software & technology development, and participation in technical networks. The indicators shown in table 1 were identified, normalized to a 0-5 scale by dividing by the maximum value across all regions.

Publications from 2011–2025 (inclusive) were considered, ensuring sufficient temporal coverage for continuous casting modelling developments including CFD, FEM/FVM, multiphase modelling, thermo mechanical coupling, and emerging digital twin applications (well represented in the literature from ~2018 onward). Examples include peer reviewed works on advanced multiphase models (e.g., CFD DBM VOF) and plant validated digital twin control systems for bloom casters, software oriented modelling papers (ProCAST, MAG-MASoft, FLOW 3D, etc.), and University/RTO outputs in casting modelling conferences.

**Tab.1** - Indicators identified for region skill classification on casting modelling.

Indicator	Description
<b>Scientific Output</b>	# of publications in the fields of CFD, FEM, FVM, CA, PFM, solidification modelling, and casting process simulation; presence of internationally cited papers and recurrent authorship in high impact metallurgical journals
<b>Institutional Presence</b>	Existence of universities, research centers, or laboratories with dedicated groups in casting modelling, metallurgical process simulation, or materials solidification research; participation in multinational research programs (e.g., EU Horizon projects, industrial consortia)
<b>Industrial Competence</b>	Activity of steel plants, technology suppliers, or engineering firms implementing advanced numerical modelling (e.g., virtual casting, mold simulation, inclusion behavior modelling); use of commercial or proprietary modelling tools at the industrial level
<b>Software &amp; Technology Development</b>	Contribution to the development of CFD/FEM software used in metallurgy (commercial or open source); specialized industrial suppliers producing simulation tools for casting and solidification.
<b>Standards &amp; Networks</b>	Participation in industrial/technical committees/networks (AIST, SEASI, etc.)

In fact, a classification based exclusively on publicly accessible evidence (peer reviewed publications, technical reports, and documented industrial case studies) may have under-represented actual competence in regions where advanced modelling is conducted predominantly within industry or in non-indexed channels.

The arising classification in table 2 below was then re-elaborated based on Real Competence / Technological Skill. A typical example is Latin America. Here, Brazil (see long tradition in metallurgical modelling, process simulation,

and computational engineering CSN, Gerdau, ArcelorMittal Tubarão, Usiminas, as well as strong steelmaking and modelling groups in Brazilian universities -USP, UFMG, UFOP, UFRGS) and Argentina (e.g., Tenaris/Techint group, Tenaris R&D in Campana and the Tenaris/university collaborations in Argentina & Italy) host highly capable industrial and R&D teams with long standing practice in continuous casting simulation and process modelling; however, much of this work is proprietary and therefore not fully reflected in bibliometric indicators.

**Tab.2** - Classification of Research and Industrial Expertise in Steel Casting Modelling.

Region	Skill based Classification	Why
<b>Europe</b>	<b>Very High</b>	Long history, strong RTO network, advanced solver development, industrial adoption.
<b>East Asia (China, Japan, Korea)</b>	<b>Very High</b>	Strong computational modelling + extensive industrial DT implementation [7].
<b>North America</b>	<b>High / Very High</b>	Strong Level 2/3 systems, CFD/ML expertise, large steel producers with modelling teams [8].
<b>South Asia (India)</b>	<b>Medium</b>	Large academic modelling base, some industrial adoption [9].
<b>South East Asia</b>	<b>Medium</b>	Growing competence but uneven across countries [10].
<b>Latin America</b>	<b>Medium</b>	Strong industrial modelling culture (Tenaris, Gerdau, Usiminas), but largely internal and unpublished—competence is higher than literature suggests [11,12].
<b>Middle East</b>	<b>Low-Medium</b>	Modernizing steel sector but modelling mostly imported.

Global Positioning of European Expertise. Europe is internationally recognized for its highly advanced capabilities in the development, validation, and industrial implementation of numerical models for steel continuous casting. Over the past decades, the European research and industrial ecosystem has consolidated a leadership position, supported by extensive scientific production, long-standing academic-industry collaboration, and structured investment through EU funding programmes such as the Research Fund for Coal and Steel (RFCFS). This combination has enabled Europe to move beyond purely theoretical modelling efforts and to translate advanced simulation methodologies into robust, operational tools widely adopted across industrial plants.

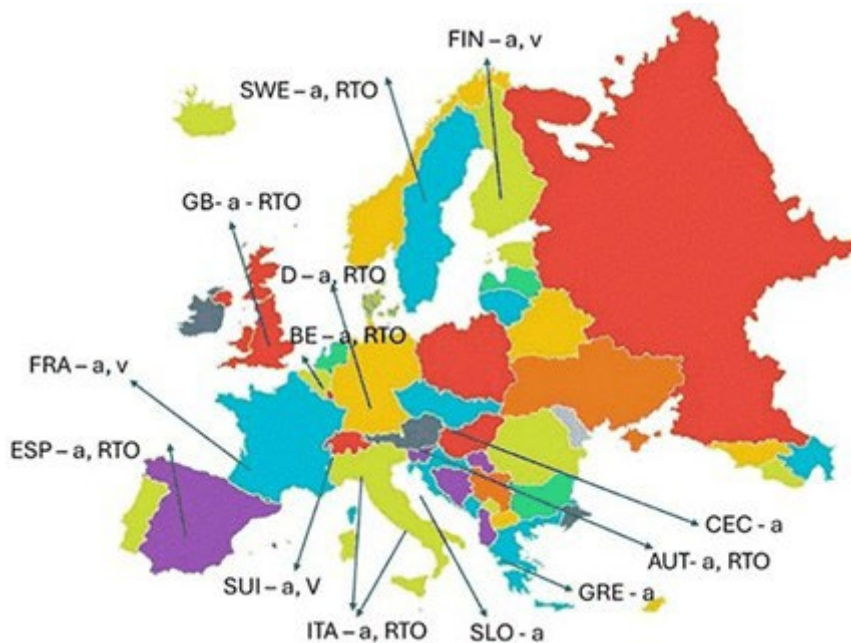
In approximately the last three decades [2], about 35 EU-funded projects have been developed involving casting modelling, roughly half of which were core R&I projects explicitly focused on modelling for steel continuous casting (Main Topic "Modelling"), with the remainder including modelling-centric accompanying measures. The most involved countries—listed in order of participation—are Germany, Italy, Austria, Spain, Belgium, Sweden, France, the United Kingdom, Finland, and the Netherlands.

The maturity of European expertise is reflected not only

in the depth of fundamental research—covering thermodynamics, fluid flow, microstructure evolution, and defect prediction—but also in its strong orientation toward applied problem-solving. European groups have been among the first to integrate high-fidelity numerical simulations, data-driven approaches, and digital-twin technologies into real production environments. As a result, Europe positions itself at a remarkably advanced level in the development, validation, and industrial deployment of numerical models for steel continuous casting, demonstrating a clear ability to bridge scientific innovation with practical implementation.

Furthermore, the widespread use of advanced computational tools, coupled with strong industrial capability in adopting simulation-based decision-making, has strengthened Europe's role as a global reference point for modelling-oriented process optimization. The integration of modelling with digital manufacturing and automation is expected to further increase the demand for specialized skills while reinforcing Europe's competitiveness in the international steel sector.

Figure 1 shows a simplified geographic elaboration after mapping the most prominent competencies in steel casting and solidification modelling categorized by country.



**Fig.1** - Regional Patterns of Casting Modelling Competence within Europe. Legend: a = academic frame; v = code developers; RTO = research centers.

This visual overview highlights the regional distribution of specialized expertise across Europe and beyond. In recent years, there has been a noticeable pivot from foundational research toward the deployment of models in industrial practice. Europe currently stands at the forefront of global expertise in this domain, facilitating a shift from theoretical exploration to applied problem-solving and operational enhancement, also supported strongly by EU funding programmes such as the Research Fund for Coal and Steel (RFCS).

As examples of cutting-edge simulations and European leadership, multi-physics coupling—turbulent mold flow (RANS/LES), heat transfer, solidification and thermo-mechanical stress—has matured into workflows that track defect precursors such as strain localization near corners and the mechanisms of oscillation-mark formation, while also resolving mushy-zone transport (Darcy law), inclusion flotation and steel-slag interactions under electromagnetic stirring (EMS). These capabilities, developed and disseminated through EU-funded activities and expert centres<sup>1</sup>, have moved beyond single-physics models to actionable tools for powder practice, taper and EMS set-point optimization [3, 6].

Moreover, Europe has pushed research-grade models into plant service via industrial digital twins. These environments connect CFD/solidification/thermo-mechanical solvers with real-time measurements to support casting-speed tuning, breakout-risk mitigation and defect prediction; they explicitly account for argon injection, curved casters, taper & friction, oscillation kinematics and EMS/brake fields, enabling fast what-if analyses aligned with production schedules [4,6].

Most challenging aspects to model. Despite the progress, several topics remain inherently difficult and are active focuses of European work: (i) crack prediction (surface/sub-surface/corner), which demands accurate high-temperature material laws, contact/friction in the mold and tightly coupled thermo-mechanical-flow solvers; (ii) oscillation marks, slag infiltration and rim build-up, which require coupling transient level fluctuations, slag rheology/solidification and mold heat-flux reconstruction; (iii) argon-laden, turbulent mold flow under EMS, where two-phase clo-

tures and electromagnetic body forces must be validated against plant measurements; and (iv) macrosegregation driven by mushy-zone permeability, shrinkage/feeding and columnar-equiaxed transitions, often addressed with CA/phase-field couplings. Progress on these fronts is documented in European-led studies and remains central to industrial defect control (examples on [3, 4, 5]).

## CONCLUSIONS

An overview has been presented of the research and development activities related to continuous casting modelling worldwide and across Europe. Europe currently stands at the forefront of global expertise in this domain, facilitating a shift from theoretical exploration to applied problem-solving and operational enhancement.

In recent years, there has been a noticeable pivot from foundational research toward the deployment of models in industrial practice. The EU funding programmes, e.g., the Research Fund for Coal and Steel (RFCS), have played a relevant role by contributing significantly to consolidating stakeholder involvement and promoting a modelling-oriented research culture.

The evolution of modelling applications has progressed from process enhancement to advanced control and, more recently, to real-time monitoring and automation. Furthermore, the integration of modelling with digital technologies is expected to drive demand for a more highly skilled workforce. In this context, the precision in simulating physical phenomena and the deepening of process knowledge have become increasingly crucial, underpinning the reliability of advanced modelling tools, supporting efficient production management, and strengthening the global competitiveness of European actors in the steel sector.

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<sup>1</sup>E.g., those involved in the METACAST project (SWERIM, BFI, K1-MET, RINA-CSM, SIDENOR)

## REFERENCES

- [1] [https://www.seaisi.org/publications/](https://www.seaisi.org/publications;);
- [2] Valorisation and dissemination of RFCS projects results and experience in steel surface quality (VALCRA). n. 847194, 2019-2020
- [3] P. E. Ramirez-Lopez, "Modelling of Continuous Casting of Steel: from virtual calculations to industrial reality", VALCRA Seminar, 2020. Available: <https://www.valcra.eu/wp-content/uploads/2020/07/VALCRA-Modelling-of-Continuous-casting-of-steel-SEMINAR-25june2020.pdf>
- [4] P. E. Ramirez-Lopez, "Digital Twin for Continuous Casting Modelling", VALCRA Webinar slides, 2020. Available: <https://www.valcra.eu/wp-content/uploads/2020/10/VALCRA-Modelling-Webinar-Sep-30th-Pavel-talk2-Digital-Twin-Continuous-Caster-FINAL.pdf>
- [5] B. G. Thomas, "Modeling of Continuous Casting", Chapter 5, University of Illinois, 2003. Available: [https://ccc.illinois.edu/PDF%20Files/Publications/03\\_AISE\\_Model\\_Ch5.pdf](https://ccc.illinois.edu/PDF%20Files/Publications/03_AISE_Model_Ch5.pdf)
- [6] S. Challapalli, L. Busolini, A. Polo, M. Ometto, "Modernization of Continuous Casting Machines in the Era of Intelligent Manufacturing", AIST Digital Transformations column, 2019. Available: <https://www.aist.org/AIST/aist/AIST/Publications/Digital%20Transformations/19-july-digital-transformations.pdf>
- [7] J. Yang, Z. Ji, W. Liu, Z. Xie, "Digital-Twin-Based Coordinated Optimal Control for Steel Continuous Casting Process". Metals, 2023, 13(4), 816. <https://doi.org/10.3390/met13040816>
- [8] Y. Fei, N. Gregurich, K. Toth, L. Yakovleva, A. Zafar, C. Zhou, "Enhanced Digital Twin Solution for Continuous Casting", AISTech 2022 Proceedings of the Iron and Steel Technology Conference, 1333-1340. 10.33313/386/153.
- [9] P. Biswas, A. Kumar, "Optimization and simulation of continuous casting process for production of stain-less steel by using Ansys CFD", AIP Conf. Proc. 3111, 040008, 2024. <https://doi.org/10.1063/5.0221474>
- [10] <https://www.seaisi.org/>
- [11] A. Gastón, G. Sánchez Sarmiento, J. S. Sylvestre Begnis, "Thermal analysis of a continuous casting tundish by an integrated fem code", Latin American applied research, 2008. 38(3), 259-266.
- [12] J. R. de Sousa Rocha, E. E. Barros de Souza, F. Marcondes, J. A. de Castro, "Modeling and computational simulation of fluid flow, heat transfer and inclusions trajectories in a tundish of a steel continuous casting machine," J. Mater. Res. Techn., 2019;8 (5):4209-4220

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