Check for updates

REVIEW

REVISED Overview of European skill and expertise in continuous casting modeling

[version 2; peer review: 2 approved with reservations, 1 not approved]

Michele De Santis[1], Edoardo D'Amanzo[1], Damiano Capobianco[1], Kersten Marx[2], Marc Koester[2], Pavel Ramirez Lopez[3], Christine Gruber[4], Alireza Atf[4], Nora Egido Perez[5], Diana Mier Vasallo[5], Arianna Gotti[6]

[1]RINA Consulting- Centro Sviluppo Materiali SpA, Roma, Italia, 00128, Italy
[2]Department Process Optimisation Iron and Steel Making, Stahlinstitut VDEh - BFI, Düsseldorf, North Rhine-Westphalia, 40237, Germany
[3]Swerim AB, Luleå, Norrbotten County, 97125, Sweden
[4]K1-MET, Linz, Austria, 4020, Austria
[5]SIDENOR I+D, Basauri, Spain, 48970, Spain
[6]Transvalor SA, Biot, 06410, France

v2 **First published:** 22 Aug 2025, **5**:251
https://doi.org/10.12688/openreseurope.20998.1
Latest published: 05 May 2026, **5**:251
https://doi.org/10.12688/openreseurope.20998.2

Abstract

Thematic and geographic mapping are presented to provide a concise overview of the domains of expertise and the relevance of associated research activities in the context of modelling for continuous casting processes. The principal areas of investigation are thermo-fluid dynamics modelling, model implementation strategies, dynamic solidification simulations, validated numerical modelling, and computational fluid dynamics (CFD). The work is not intending to represent a critical review focusing on the research aspect of continuous casting simulation, but more for an overview and summary of different European affiliations activity. In steel casting, the accurate representation and simulation of critical physical phenomena, namely heat transfer, fluid flow, and solidification, are fundamental for optimizing the process performance and ensuring the integrity of the final product. To this end, advanced numerical methodologies, such as the Finite Element Method (FEM), Finite Volume Method (FVM), Cellular Automata (CA), and Phase Field Method (PFM), have been extensively employed. A brief classification of these computational approaches is provided and organized according to their respective frameworks and techniques, with mentioning at a glance. Not exhaustive - of relevant Institutions involved in R&D and the fields they have been focusing on.

Open Peer Review

Approval Status ✗ ? ?

	1	2	3
version 2 (revision) 05 May 2026			
version 1 22 Aug 2025	✗ view	? view	? view

1. **Rüdiger Schwarze**, TU Bergakademie Freiberg, Freiberg, Germany
2. **Kun Dou**, Central South University, Changsha, China
3. **Wangzhong Mu**, Lulea University of Technology Department of Engineering Sciences and Mathematics (Ringgold ID: 407846), Luleå, Sweden

Any reports and responses or comments on the article can be found at the end of the article.

Keywords
Continuous Casting, Modelling, Skill map, Europe, Computational Fluid Dynamics

Corresponding authors: Michele De Santis (michele.desantis_csm@rina.org), Edoardo D'Amanzo (edoardo.damanzo@rina.org), Damiano Capobianco (damiano.capobianco@rina.org), Kersten Marx (kersten.marx@bfi.de), Marc Koester (marc.koester@bfi.de), Pavel Ramirez Lopez (pavel.ramirez.lopez@swerim.se), Christine Gruber (christine.gruber@k1-met.com), Alireza Atf (alireza.atf@k1-met.com), Nora Egido Perez (nora.egido@sidenor.com), Diana Mier Vasallo (diana.mier@rina.org), Arianna Gotti (arianna.gotti@transvalor.com)

Author roles: De Santis M: Conceptualization, Investigation, Methodology, Resources, Supervision, Validation, Writing – Original Draft Preparation, Writing – Review & Editing; **D'Amanzo E**: Investigation, Methodology, Resources, Validation; **Capobianco D**: Investigation, Methodology, Validation; **Marx K**: Investigation, Methodology, Supervision, Writing – Review & Editing; **Koester M**: Investigation, Methodology, Validation; **Ramirez Lopez P**: Formal Analysis, Investigation, Methodology, Resources, Supervision, Writing – Review & Editing; **Gruber C**: Investigation, Methodology, Resources, Supervision, Writing – Review & Editing; **Atf A**: Investigation, Methodology, Supervision, Writing – Review & Editing; **Egido Perez N**: Investigation, Methodology, Resources, Supervision, Writing – Review & Editing; **Mier Vasallo D**: Investigation, Methodology, Validation; **Gotti A**: Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

Grant information: This study was carried out with a financial grant from the Research Fund for Coal and Steel of the European Community. The authors would like to thank the EU for supporting the ongoing METACAST project (contract number 101155952) for disseminating the main outcomes in the field of casting modelling.

Copyright: © 2026 De Santis M *et al*. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

How to cite this article: De Santis M, D'Amanzo E, Capobianco D *et al.* **Overview of European skill and expertise in continuous casting modeling [version 2; peer review: 2 approved with reservations, 1 not approved]** Open Research Europe 2026, **5**:251 https://doi.org/10.12688/openreseurope.20998.2

First published: 22 Aug 2025, **5**:251 https://doi.org/10.12688/openreseurope.20998.1

REVISED **Amendments from Version 1**

The revision made intended to follow the reviewers indication, overall:

- in giving more 'scientific' character to the document
- in clarifying the criteria to classify the ìgeographic' skill,
- in mentioning with appropriate references the Centers deserving mention in the field (also detailing those not properly mentioned in the first version (e.g. rev 1)
- in adding a part referring to AI/ML issues as future trend (e.g. rev. 2)

Details as follows.

Abstract: clarifying the scope of the paper:

1) Overall, attempt to fix a point raised from all revisors: the paper , to cite revisor 2, '*It reads more like a project report or a directory listing rather than a comprehensive scholarly synthesis*' as well as reviewer 1 (it is not a 'critical review' discussing technical aspect, as also mentioned by reviewer 2 (***The reviewer can understand this is not a critical review focusing on the research aspect of continuous casting simulation, but more for an overview and summary of different European affiliations' activity.***) but is a review of what existing, even though the paper quality should have been improved, as properly asked by all the reviewers): *There is no critical discourse, no well-defined research question, and no clear scientific framework. Instead, the paper presents a mere enumeration of simulation methods and tools—without any explanation of their physical foundations, application domains, or limitations. This bullet-point-style listing reads more like a technical product catalog than a scholarly contribution.*
2) Afterwards: skipped the reference to the METACAS project partners, mentioned only in the acknowledgements (remark of revisor 1: '*commendable, the manuscript in its current form lacks the scientific rigor, critical depth, and structural coherence expected for a review article.* ***It reads more like a project report or a directory listing rather than a comprehensive scholarly synthesis***')

Overview:

1) mentioning of for continuous casting *supporting numerical modelling,. e.g. Mold Crack Simulator (MCS), Single/Double Hot Thermocouple Technique (SHTT/DBTT), High-Temperature Confocal Laser Scanning Microscopy (HT-CLSM), etc. which use to simulate different*... as asked by revisor 3
2) mention of CALPHAD... (to comply with the remark of revisor 2 '***For example, CALPHAD (CALculation of PHAse Diagrams) is coupling with the CFD simulation to use in some solidification/casting research; AI-based branches, e.g. machine learning, are used to predict the solidification microstructure, and defects (cracks, macro segregation, porosity, inclusion, etc.) for the quality control of casting lab, etc.***')

Scenario:

Rewritten part with world skill classification and criteria explanation (in Table 1 and 2), also with quantitative aspects, to comply with indication of Revisor 1 (especially) and revisor 3. For further sake of clarity, Figure 1 replaced by a table (Table 3).

European Expertise:

1) Clarification about some centers mentioned, just as example to comply with the remark of reviewer 1: '. **No evaluation framework or selection process is provided, making the list appear arbitrary to the reader.**' Also re-edited the Table legenda (Now Table 4) on the correspondence between Countries and Centers skill. For the elaboration of classification (role of papers and 'known' skill) see also the second issue in point 3) below (why skill assessment via only paper production can underestimate a Center skill).
2) Indication of relevant publications for each Center indicated: djusted to follow a concern from reviewer 1 '***expanding the scope of literature...***' and reviewer 3: ***each university/institute can introduce 1-2 representative research results/ achievements (Figures or Tables can be a better way), which could attract the audience more, and this will also let the readers know each party's expertise***- Moreover, addition to comply with reviewer 1 indication: '***Most notably, the state-of-the-art liquid metal model casting facilities at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR), which are globally acknowledged as reference installations, are not mentioned at all—an omission that severely compromises the credibility of the selection***'.
2) Overall, skipped the 'written list' country by country, that let the section to provide for '***...descriptions of the selected institutions (...) inadequate: they are presented exclusively in bullet points and resemble promotional material rather than a substantive, scientific analysis.***' Moreover, a sort of disclaimer concerning the amount of publications available is given prior to Figure 3 (confidentiality constraints could have prevented dissemination of some findings from modelling use).

New Section On future trends and machine learning:

1) Inserted to fix a point raised by Revisor 2, in particular, the suggestion to account for a reference paper (Materials. 2024;**17** (13): 9) and from reviewer 1: ***Instead, the paper lacks a thorough literature review and fails to engage with contemporary developments, key challenges, or methodological innovations. Notably, the growing use of machine learning—a central trend in modern materials science and process optimization—is mentioned only superficially, without any discussion of its relevance, application potential, or limitations. This superficial treatment of current research trends suggests that the manuscript is not grounded in a rigorous engagement with the existing literature***.

Conclusions:

1) AI-ML aspects also mentioned (see remarks above from reviewers 1 and 3).

Any further responses from the reviewers can be found at the end of the article

Objectives

After providing a brief overview of casting modelling topics and tools, the document aims to map the worldwide continuous casting modelling landscape, the European positioning within it, and current and future trends.

Overview: topics and tools

This section provides insights into Computational Techniques based on the physical phenomena involved in steel casting and solidification.[1–11] So, it is worth mentioning that there are also some important experimental simulation research activities that are rather important for continuous casting supporting numerical modelling, e.g. Mold Crack Simulator (MCS), Single/Double Hot Thermocouple Technique (SHTT/DBTT), High-Temperature Confocal Laser Scanning Microscopy (HT-CLSM), etc. which use to simulate different phenomenon of dendrite formation, crystallization of mold flux, non-metallic inclusion motion behavior during casting, etc. These items are beyond the scope of such document, whilst relevant in most cases in contributing to their development, consistency and validation.

a) Numerical methods for modelling steel casting and solidification

Finite Element Method (FEM). The finite element method (FEM)[1] is a powerful numerical technique that discretizes a continuum domain into smaller linked elements and nodes *(i.e. finite elements)*, enabling the solution of complex partial differential equations governing physical phenomena in steel casting and solidification. Its applications in this context include the following.

- Thermal Analysis: FEM was employed to simulate heat transfer during solidification, calculate temperature distributions within the casting and mold, and predict solidification paths. This facilitates the identification of potential defects, such as hot spots.
- Stress and Deformation Analysis: FEM supports the prediction of thermally induced stresses, which may lead to deformation or cracking during solidification.
- Solidification Modelling: FEM enables the simulation of the solidification process, including the formation and growth of the solid shell in continuous casting.
- Coupled Thermo-Mechanical Modelling: Advanced implementations, such as coupled thermomechanical FEM, allow for the simulation of interactions between thermal and mechanical phenomena during solidification.
- Coupled Thermal and Fluid Flow Simulations: Advanced implementations, such as implicit coupled thermal and CFD with an Arbitrary Eulerian-Lagrangian approach, allow the simulation of the smooth transition from the liquid to the solid and compute the velocity of the liquid metal, which turns into casting speed in the solid material.[2]

Finite Volume Method (FVM). It divides[3] the spatial domain into small control volumes (i.e., cells) and is particularly effective in solving conservation laws. It is widely used in modelling the fluid flow and heat transfer in steel casting processes. The key applications include the following.

- Fluid Flow Simulation: FVM is used to model molten steel flow within molds, providing insights into thermal and flow conditions at the liquid–solid interface and identifying potential defects such as air entrapment or inclusions.

- Heat Transfer Analysis: FVM helps determine cooling rates and solidification patterns, which are critical for controlling the microstructure and mechanical properties.

- Solidification Modelling: This provides detailed insights into the temperature evolution and phase transformations during the casting process.

Cellular Automata (CA). They are computational models[4] used to simulate complex systems using discrete cells governed by local rules based on the states of neighboring cells. In steel solidification, CA models are particularly effective in predicting grain structure evolution by capturing the nucleation and growth phenomena.[5]

Phase Field Models (PFM). These models are set up and used to investigate the phenomena of flow scenarios for different regions with different dynamics, and the impact on the formation of microstructure, based on computations of the thermodynamic and kinetic properties of the flow. These models can capture the dynamics of solidification and the effects that lead to defects in cast products.[6] These approaches usually consider a wide range of chemical reactions due to elements present in the steel and rely on simple and fast calculations, as opposed to the FEM or FVM approaches described above.

b) Key phenomena in steel casting modelling

They are briefly listed and referenced in [7] as follows:

Heat Transfer. Heat transfer governs the solidification rate and significantly influences the grain structure. Thermal gradients determine the morphology of the solidification front (e.g., planar, cellular, or dendritic). Accurate modelling must incorporate conduction, convection, and radiation to account for the heat exchange in the mold, convective currents in the molten steel, and radiative losses at the surface.

Fluid Flow. Fluid flow affects the heat transfer, solute distribution, and inclusion behavior. Key mechanisms include natural and forced convection (e.g., via electromagnetic stirring) and buoyancy-driven flow, which influence the flotation of nonmetallic 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. Solidification involves the transformation from liquid to solid, which is influenced by thermal gradients, cooling rates, and alloy composition. This process determines 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. During solidification, solutes partition between the solid and liquid phases, leading to micro-segregation. This phenomenon affects the mechanical and chemical properties of the final product and must be carefully modelled to ensure quality control.

Precipitates, Inclusions and Defect Formation. Precipitates and inclusions (e.g., oxides and sulfides) and other defects (e.g., porosity and cracks) form owing to steel chemistry, re-oxidation, flow conditions, and thermal gradients. CFD models, when coupled with thermodynamic calculations, can predict the inclusion behavior and help mitigate defect formation.

Modelling Tools and Technological Advances. The development and adoption of commercial and open-source computational tools have significantly advanced the modelling of steel casting processes. For example, CALPHAD (CALculation of PHAse Diagrams) is coupling with the CFD simulation to use in some solidification/casting research; AI-based branches, e.g. machine learning, are used to predict the solidification microstructure, and defects (cracks, macro segregation, porosity, inclusion, etc.) for the quality control of casting lab, etc. These tools implement momentum, heat, and solute conservation equations in user-friendly interfaces

- Commercial General purpose: ABAQUS, ANSYS Fluent, MSC.MARC.

- Commercial process-specific software: ProCAST, MAGMASOFT, THERCAST®.

- Open-source software: OpenFOAM.

- CALPHAD-based software: Thermo-Calc, MatCalc, Micress, JMatPro.

- Python-based frameworks.

Emerging Trends and Future Directions. Recent innovations in steel casting and solidification[8] modelling include the following.

- Advanced Computational Techniques: Multiphysics simulations[9] and High-Performance Computing (HPC) enable high-resolution, large-scale simulations of the entire casting process.
- Machine Learning (ML)[10] and Artificial Intelligence (AI).[11] These technologies are increasingly being used to predict casting defects, optimize process parameters, and analyze large datasets from simulations and experiments. Data-based approaches can significantly improve either the computational cost or the quality of the results.
- Real-Time Monitoring: Digital Twins.[12] Digital twins act as virtual casting process replicas, enabling real-time monitoring and optimization. They are supported by in situ monitoring technologies, including advanced sensors and imaging systems, to achieve real-time data on temperature, solidification occurrence, and defect formation.

The technical trend can be summarized in Figure 1, taken from a former analysis conducted in an RFCS project,[13] which focused more on defect occurrence in as-cast products.

Scenario

World mapping. A classification was proposed aimed at offering a comprehensive view of the ecosystem that supports numerical modelling in the steel casting sector and highlighting the maturity and integration of modelling practices across academic, industrial, and research environments worldwide.[14]

To establish the regional classification, a set of quantitative criteria was defined using indicators derived from peer-reviewed technical literature and reproducible bibliometric sources (Scopus and Web of Science, 2011–2025). These indicators capture scientific output, the presence of research institutions, industrial know-how (including plant-validated modelling and digital-twin applications), software and technology development, and involvement in technical or industrial networks. All indicators listed in Table 1 were normalized to a 0–5 scale by dividing each regional value by the global maximum.

The bibliometric analysis covered publications from 2011 to 2025 (inclusive), providing sufficient temporal depth to map the evolution of continuous casting modelling, including CFD, FEM/FVM, multiphase flow formulations, thermo-mechanical coupling, and recent digital-twin approaches, which have gained significant traction since approximately

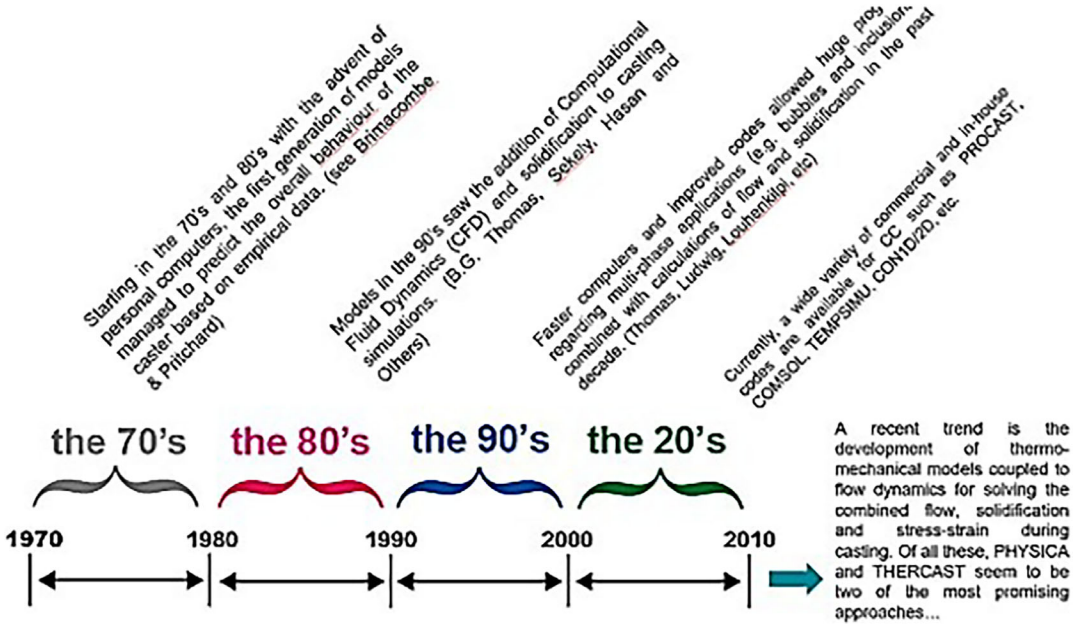


Figure 1. Trend of modelling of steel casting and solidification from 70's onwards.[13]

Table 1. Indicators used for regional skill classification in casting modelling.

Indicator	Description
Scientific Output	Number of publications in CFD, FEM, FVM, CA, PFM, solidification modelling, and casting process simulation; presence of internationally cited papers and recurring authorship in high-impact metallurgical journals.
Institutional Presence	Existence of universities, research centres, or laboratories with dedicated groups in casting modelling, metallurgical process simulation, or solidification research; participation in multinational research frameworks (e.g., EU Horizon programmes, industrial consortia).
Industrial Competence	Activity of steel producers, technology suppliers, or engineering firms employing advanced numerical modelling (e.g., virtual casting, mould-flow simulation, inclusion-transport modelling); use of commercial or proprietary modelling tools at plant level.
Software & Technology Development	Contributions to the development of CFD/FEM software used in metallurgical applications (commercial or open-source); presence of specialized industrial suppliers creating simulation tools for casting and solidification.
Standards & Networks	Participation in industrial or technical committees and networks (e.g., AIST, SEAISI).

2018. The corpus includes peer-reviewed studies on advanced multiphase solvers (e.g., CFD-based DBM and VOF schemes), plant-validated digital-twin control systems for bloom casters, software-oriented modelling contributions (e.g., ProCAST, MAGMAsoft, FLOW-3D), and outputs from universities and RTOs presented in specialized casting-modelling conferences.

The expertise levels are categorized as follows:

- **Very High:** extensive incorporation of modelling methodologies within both academic and industrial domains, with presence of pioneering software developers and mature research and development infrastructures.
- **High:** strong scientific output and widespread industrial implementation, particularly evident among leading manufacturers and technology suppliers.
- **Medium–High:** developing modelling capabilities supported by prominent academic institutions and increasing engagement from industrial stakeholders.
- **Medium:** modelling practices are established but exhibit variability, often confined to specific organizations or regional clusters.
- **Low–Medium:** low progress in modelling development, with a predominant reliance on imported technologies and intermittent domestic initiatives.
- **Low:** poor or non-existent modelling frameworks, with substantial dependence on external expertise and technology.

Concerning the papers found on the net, a classification was guessed based on the numbers of contributions as in Table 2.

A classification based solely on publicly accessible information—such as peer-reviewed publications, technical reports, or documented industrial case studies—inevitably underrepresents regions where advanced modelling is primarily conducted within industry or through non-indexed channels.

For this reason, the classification in Table 3 was further refined by incorporating an assessment of actual technological capability and industrial practice. Latin America provides a representative example. Although bibliometric indicators suggest a moderate level of activity, countries such as Brazil and Argentina host highly experienced modelling communities. Brazil has a long tradition in metallurgical and computational engineering (e.g., CSN, Gerdau, Arcelor-Mittal Tubarão, Usiminas; and strong academic groups at USP, UFMG, UFOP, UFRGS). Argentina benefits from the longstanding modelling culture within the Tenaris/Techint group, including Tenaris R&D in Campana and multiple Tenaris–university collaborations in Argentina and Italy. However, much of this work is proprietary, explaining the discrepancy between bibliometric signals and actual regional expertise.

Table 2. Indicators derived from regional publication in casting modelling.

Region	% of Total Papers	Score
East Asia	23%	Very High
Europe	23%	Very High
South Asia	23%	Very High
North America	15%	High
South America	8%	Medium
Middle East	8%	Medium (see text below)
South-East Asia	<1%	Emerging
Oceania	<1%	Emerging
Africa	<1%	Emerging

Table 3. Classification of research and industrial expertise in steel-casting modelling.

Region	Skill-Based Classification	Reason
Europe	Very High	Long-standing tradition, extensive RTO network, advanced solver development, widespread industrial deployment.
East Asia (China, Japan, Korea)	Very High	Strong computational modelling culture combined with broad industrial adoption of digital-twin technologies.
North America	High	Mature Level-2/3 automation, strong CFD/ML competence, and large steel producers with dedicated modelling teams.
South Asia (India)	Medium	Broad academic base and increasing, though uneven, industrial adoption.
South-East Asia	Medium	Expanding capabilities but with significant variability across countries.
Latin America	Medium	Strong industrial modelling tradition (e.g., Tenaris, Gerdau, Usiminas), though largely internal and insufficiently represented in the literature.
Middle East	Low–Medium	Rapidly modernizing steel sector; modelling expertise mainly imported.

As a result, the classification/assessment here presented is based on the number of 'KPI' reached based on the info gained so far on these aspect: 1) Modelling developing capability; 2) Link with dedicated industries (for validation, application) and academies (network boosting info dissemination, also via dedicated projects at Institutional Level; 3) Application at a broad level in the industry frame; This classification offers a strategic lens through which to assess the global landscape of modelling expertise, facilitating the identification of prospective partnerships and avenues for knowledge exchange within the international steel sector.

European expertise at a glance

An overview of the European skill mapping

Based on the assessment in Table 4, Europe is well positioned in the framework. Then, this section provides an overview of European academic and research institutions actively engaged in the development and dissemination of modelling techniques for steel casting and solidification.

In Figure 2, as a first reference, the countries participating in the METACAST project are highlighted as well as the mentioned Centers in Table 1, as representative and non-exhaustive examples of the European expertise. Additionally, institutions from the United Kingdom were included to illustrate further contributions from countries whose general characteristics are summarized in Table 4. For each Country, references in the field are recalled. This expanded perspective aims to showcase the diversity and depth of modelling capabilities across Europe and to underline the collaborative nature of ongoing research efforts in this domain.

Table 4. Skill in steel continuous casting modelling per country, referring to academia or R&D centers *(non-exhaustive). Same legenda of Figure 2.*

Country	Reference	Type	Skill	Main activity
France[2,15]	CEMEF	A	Multiphysics, multiscale solidification modeling	Papers, support to codes
	Transvalor SA	V	Multiphysics, multiscale casting and solidification software vendor	industrial application (problem solving)
Spain[16–21]	SIDENOR I + D	RTO	Flow & solidification modeling	Papers, industrial application (problem solving)
Switzerland[22]	ETH- Poly. Of Zurich	A	Flow modeling	Papers
	CALCOM	V	solidification code vendor	industrial application (problem solving)
Italy[13,14,23–26]	Politecnico di Milano	A	Flow & solidification modeling	Papers
	Rina Consulting - CSM	RTO	Flow & solidification modeling	Papers, problem solving –numerical and physical tools
Slovenia[27]	Ljubljana University	A	Flow & solidification modeling	advanced flow models (LES) coupled to solidification
Greece[28]	Athens University	A	Flow modeling in mould	advanced flow models (LES) coupled to solidification
Austria[29–44]	Montanuniversität Leoben	A	Flow & solidification modeling	advanced flow models coupled to solidification/clogging
	Johannes Kepler University	A	Flow modeling	advanced flow models in casters
	K1-MET	RTO	Flow modeling	advanced flow models in casters
Czechia[45]	Ostrava University	A	Flow & solidification modeling	advanced flow models coupled to solidification
Germany[46–51]	RWTH Aachen	A	Flow modeling	advanced flow models (tundish)
	VDEh-Betriebsforschungsinstitut GmbH	RTO	Flow & solidification modeling	Papers, problem solving –numerical and physical tools, milestone info for models insight and development Advancing in fundamentals and high-level validation (lab): use of real liquid metals, advanced flow diagnostics, full scale EM actuator testing Multiphysics model validation
	Zentrum - Zentrum Dresden-Rossendorf (HZDR)		state-of-the-art liquid metal model casting facilities:	
Belgium[52]	CRM	RTO	Mould Flow modeling	Pilot plants (mould alloying)
Sweden[53–71]	SWERIM KTH	RTO A	Flow & solidification modelling, Thermodynamics, refractories	Papers, problem solving –numerical and physical tools
Finland[72–75]	Oulu University	A	Flow & solidification modeling	Papers, problem solving –
	CASIM consulting	V	Flow & solidification modeling	Papers, problem solving –coupling with thermo-chemistry
UK[76]	MPI (formerly CORUS)	RTO	Modeling validation (pilot plants)	Papers, problem solving
	Imperial College Sheffield University Warwick University	A	Flow modelling, thermodynamic modelling, material properties	Papers, partner in EU funded projects

Open Research Europe 2026, 5:251 Last updated: 19 JUL 2026

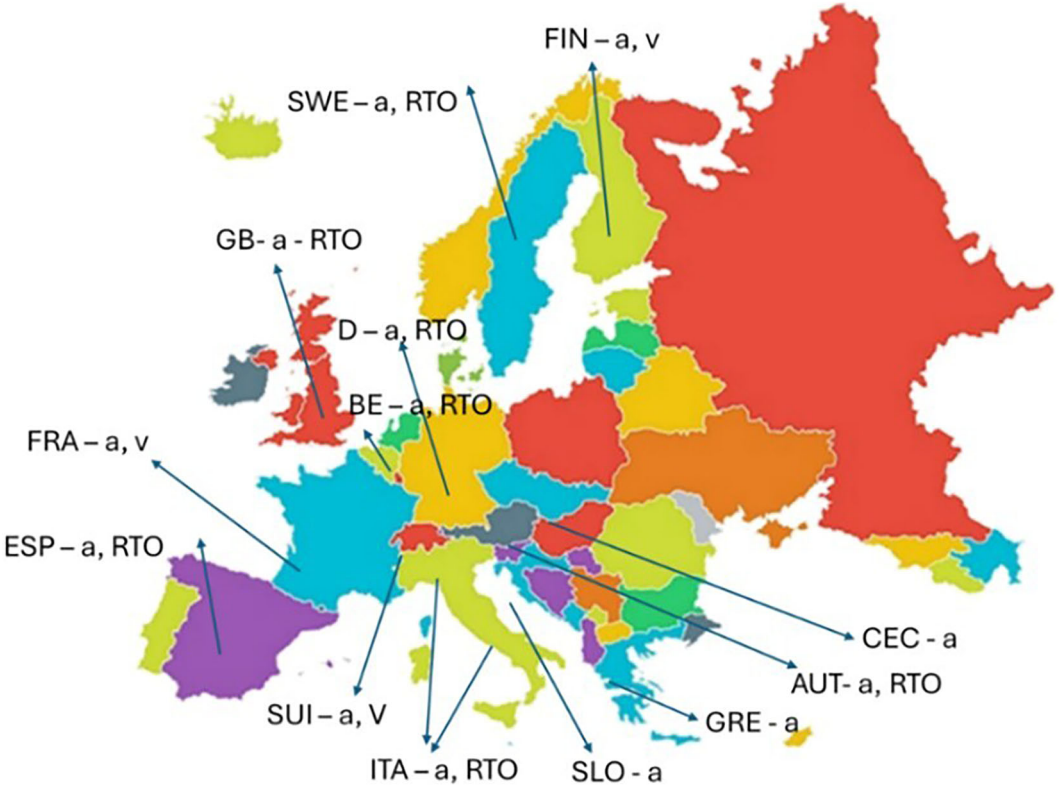


Figure 2. Geographic Distribution of European casting modelling expertise. Legenda: a- academic frame; v = code developers; RTO = research centers.

Efforts within the European Funding Programmes: RFCS

In relation to EU-funded initiatives, a relevant role is played by European Commission co-financed projects involving continuous casting modelling with qualified participation of project partners. EU programs have significantly supported this topic. To give an idea, Figure 3 gives how the 'call priorities" (the main topics the funding programmes were focused on) have evolved in the last 15 years, while Figure 4 highlights the technical/technological trend relating to modelling development.[13] This shows how EU efforts and support are currently well-aligned with stakeholders' needs and technical trends. Then, modelling trends should follow this way, namely, in the frame of enhanced and more complex (e.g., multiphysics) description and with shorter calculation times also thanks to increasing computing power.

A comprehensive the list of the RFCS (Research fund of Coal and Steel) projects carried out focused on or involving casting modelling in the last 25 years is shown in 13. Most European projects demonstrated a satisfactory degree of success, both in terms of implementation during their execution and, in several cases, through continued uptake after their completion.

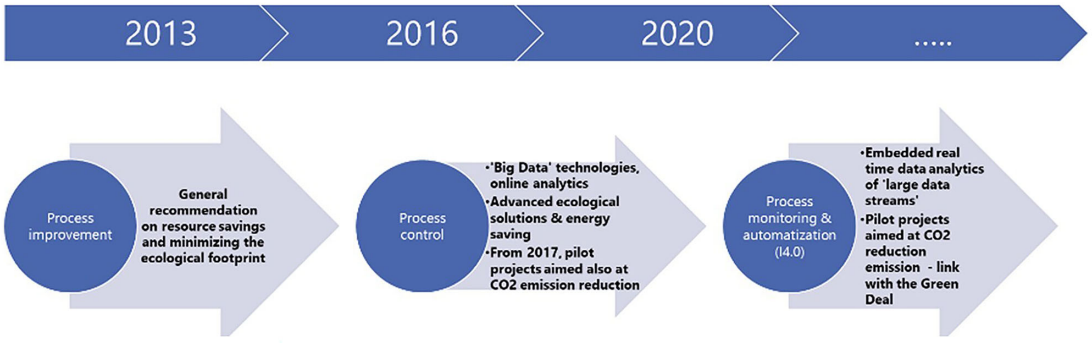


Figure 3. Evolution of the RFCS 'call priorities'.[13]

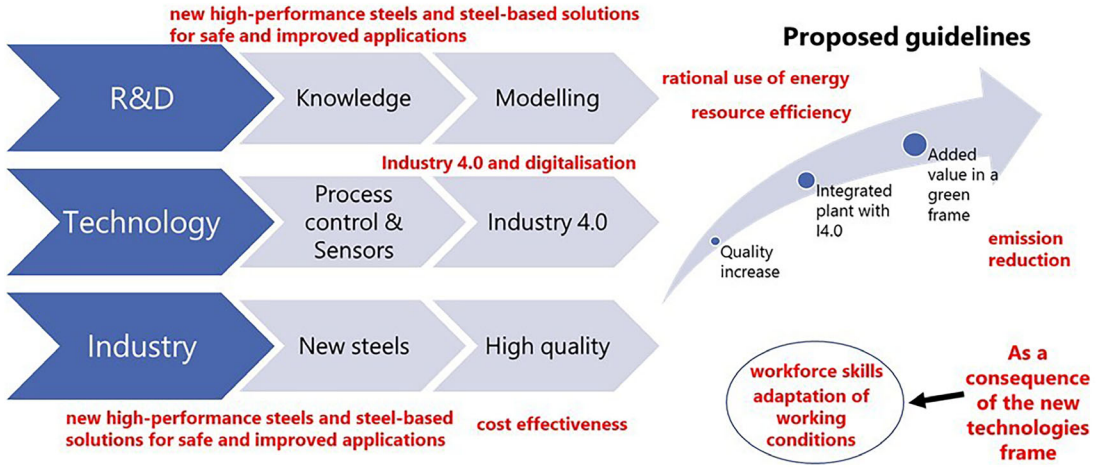


Figure 4. Technical/technological trend in casting process evolution.[13]

These outcomes indicate that the models and tools developed held substantial relevance for industrial stakeholders. However, systematic tracking of follow-up activities remains limited, and comprehensive evaluations of the economic impact generated by the deployed models are often unavailable. Consequently, it is difficult to determine whether the projects produced limited economic benefits or whether such benefits were not recorded or disclosed by industrial partners—possibly due to confidentiality constraints or because assessments took place at a later stage. This highlights a broader challenge in consistently evaluating project impact, despite the strong industrial value demonstrated during project implementation.

Ongoing issues and Future trends: machine learning

Continuous casting of steel is intrinsically governed by interacting phenomena spanning multiple spatial and temporal scales [15,27,28,45,52,22,72–80], from turbulent flow and heat transfer at the strand scale to microstructural evolution and defect formation during solidification. Multiscale simulation frameworks have therefore been developed to link macroscopic transport phenomena with mesoscopic and microscopic material descriptions, enabling improved prediction of process evolution and product quality compared with single-scale models. In recent years, these multiscale approaches have increasingly been combined with machine learning (ML) techniques, particularly in the context of process monitoring, control and optimisation, leading to the emergence of hybrid physics-based and data-driven modelling strategies.

At the macroscopic level, numerical models based on computational fluid dynamics and thermo-mechanical analysis are routinely employed to describe melt flow, heat extraction, shell growth and stress development in the mold and secondary cooling zones. Outputs from these models—such as local cooling rates, temperature gradients and solidification times—are transferred to mesoscopic solidification models, which capture dendritic growth, solute redistribution and mushy-zone behavior. This hierarchical information exchange represents the backbone of multiscale simulation in continuous casting and remains essential for understanding the physical origin of defects and the influence of process parameters. However, the computational cost associated with high-fidelity multiscale simulations limits their direct use in real-time control applications.

To overcome these limitations, machine learning has been introduced as a complementary modelling layer, rather than as a replacement for physics-based approaches. In this paradigm, numerical simulations and industrial data are used to train ML models that act as fast surrogates for selected components of the multiscale framework. These surrogate models can reproduce key outputs of numerical simulations—such as temperature fields, shell thickness or metallurgical length—with high accuracy while enabling prediction times compatible with online monitoring and control. Representative studies have demonstrated the feasibility of deep-learning-based surrogates for near real-time estimation of internal process states, supporting adaptive adjustment of operating parameters during continuous casting operations.

A significant research trend is the development of **hybrid or mechanism-data-driven models**, in which physical knowledge derived from numerical modelling is explicitly embedded into the ML workflow. This integration may take the form of physics-informed inputs, physically constrained loss functions, or training datasets generated by parametric numerical simulations. Such approaches enhance robustness, improve extrapolation capability beyond the range of available plant data, and partially address interpretability concerns that often limit industrial adoption of purely

data-driven models. Recent reviews highlight that these hybrid frameworks are increasingly dominant in applications related to defect prediction, abnormal condition detection and process parameter optimisation in continuous casting.

From a process optimisation and control perspective, ML-based surrogate models derived from multiscale simulations enable efficient exploration of high-dimensional process spaces. When coupled with optimisation algorithms such as Bayesian optimisation or evolutionary strategies, these models support adaptive control of casting speed, secondary cooling intensity and soft-reduction parameters. This integrated modelling-optimisation loop forms the basis of emerging digital-twin concepts for continuous casting, where numerical models, ML surrogates and real-time plant data are combined within a unified framework for decision support and process stabilization.

Despite the rapid progress achieved, several challenges remain. Key issues include the quality and representativeness of industrial data, the transferability of ML models across different steel grades and caster configurations, and the need for improved interpretability and reliability in safety-critical control applications. These challenges further reinforce the importance of multiscale numerical modelling as a reference framework for ML development and validation. Current research efforts therefore increasingly focus on data-efficient learning strategies, physics-informed neural networks and hybrid digital-twin architectures, which align closely with European priorities in digitalisation, sustainability and low-carbon steel production.

Conclusions - status and perspectives

This document provides a concise overview of the distribution of research and development efforts across Europe in the domain of continuous casting modelling. Notably, significant contributions have emerged from Western European countries, especially research centers, largely supported by European-level funding programmes. These initiatives have acted as catalysts, reinforcing the engagement of key stakeholders and fostering a robust modelling culture.

Recent trends indicate a strategic shift in focus toward the practical application of models, particularly their integration into process control systems and artificial intelligence (AI)-driven tools. The current state of knowledge in Europe is among the most advanced globally, enabling a transition from fundamental research to problem-solving and operational optimization. This evolution closely aligns with the thematic priorities of the Research Fund for Coal and Steel (RFCS) over the past 15 years.

Progression has moved from process improvement to process control and, more recently, toward process monitoring and automation. These developments reflect the growing demand for enhanced steel quality and the imperative to meet environmental and economic sustainability objectives. In addition, the trend of coupling modelling with digitalization will inevitably bring about the need for higher worker skills. In particular, coupling with AI-ML approaches represent the emerging trends, up to including the increased use of physics-informed neural networks, hybrid digital twins and data-assisted multiscale frameworks that integrate modelling across process, microstructure and control scales. These developments align closely with European strategies on digitalisation, sustainability and low-carbon steel production, where data-efficient, interpretable and physically grounded modelling approaches are strongly prioritized.

In this context, the accurate modelling of physical phenomena and a deeper understanding of the casting process have become increasingly critical. Such advancements are essential to ensure the reliability of sophisticated modelling tools, support effective production management, and reinforce the competitiveness of European stakeholders in the global steel industry.

Ethics and consent statement

Ethical approval and consent were not required.

Data and software availability

No data or software are available.

References

1. Lewis RW, Roberts PM: **Finite element simulation of solidification problems.** *Applied Scientific Research.* 1987; **44**: 61–92.
Publisher Full Text

2. Forestier R, Costes F, Jaouen O, *et al.*: **Finite element thermomechanical simulation of steel continuous casting.** *MCWASP XII, Modelling of Casting, Welding, and Advanced Solidification*

Processes, MS (The Minerals, Metals & Materials Society). 2009.
Reference Source

3. Chen Z, Li Y, Zhao F, *et al.*: **Progress in numerical simulation of casting process.** *Measurement and Control.* 2022; **55**(5–6): 257–264.
Publisher Full Text

4. Zhi Y, Jiang Y, Ke D, *et al.*: **Review on Cellular Automata for microstructure simulation of metallic materials.** *Materials (Basel).* 2024; **17**(6): 1370.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

5. Andersson C, Lindback A: **Modeling the evolution of grain texture during solidification of laser-based powder bed fusion manufactured alloy 625 using a Cellular Automata Finite Element model.** *Metals.* 2023; **13**(11): 1846.
Publisher Full Text

6. Tourret D, Liu H, Llorca J: **Phase-field modeling of microstructure evolution: recent applications, perspectives and challenges.** *Prog Mater Sci.* 2022; **123**(12): 100810.
Publisher Full Text

7. Louhenkilpi S: **Chapter 1.10 - Continuous casting of steel.** *Treatise on Process Metallurgy (Second Edition) -Volume 3: Industrial Processes.* 2024; 343–383.
Publisher Full Text

8. Guthrie RIL, Isac MM: **Continuous casting practices for steel: past, present and future.** *Metals.* 2022; **12**(5): 862.
Publisher Full Text

9. Zappulla MLS, Cho SM, Koric S, *et al.*: **Multiphysics modeling of continuous casting of stainless steel.** *J Mater Process Technol.* 2020; **278**: 116469.
Publisher Full Text

10. Cemernek D, Cemernek S, Gursch H, *et al.*: **Machine learning in continuous casting of steel: a state-of-the-art survey.** *J Intell Manuf.* 2022; **33**: 1561–1579.
Publisher Full Text

11. Koric S, Abueidda DW: **Deep learning sequence methods in multiphysics modeling of steel solidification.** *Metals.* 2021; **11**(3): 494.
Publisher Full Text

12.
Reference Source

13. **Valorisation and dissemination of RFCS projects results and experience in steel surface quality (VALCRA).** n. 847194, 2019-2020.
PubMed Abstract | **Reference Source**

14. De Santis M, *et al.*: Modeling of Steel Continuous Casting: Overview of European Knowledge and Its Global Standing, La Metallurgia Italiana, to be published, March 2026.

15. Materials Processes Institute. Training – Casting. 2026.
Publisher Full Text

16. Yang H, Ramirez Lopez PE, Mier Vasallo D, *et al.*: **Designing non-newtonian mold powders and optimization of process for continuous casting of billet.** *Steel Res Int.* 2022; **93**(3): 2100379.
Publisher Full Text

17. Wang S, Alvarez De Toledo G, Välimaa K, *et al.*: **Magnetohydrodynamic phenomena, fluid control and computational modelling in the continuous casting of billet and bloom.** *ISIJ Int.* 2014; **54**(10): 2273–2282.
Publisher Full Text

18. Yang H, Ramirez Lopez PE, Mier Vasallo D: **New concepts for prediction of friction, taper, and evaluation of powder performance with an advanced 3D numerical model for continuous casting of steel billets.** *Metall Mater Trans B.* 2021; **52**: 2760–2785.
Publisher Full Text

19. Cabalín LM, Delgado T, Ruiz J, *et al.*: **Stand-off Laser-Induced Breakdown Spectroscopy for steel-grade intermix detection in sequence casting operations. At-line monitoring of temporal evolution versus predicted mathematical model.** *Spectrochim Acta B At Spectrosc.* 2018; **146**: 93–100.
Publisher Full Text

20. Yang H, Kesavan S, Mier Vasallo D, *et al.*: **The influence of thermo-physical properties on slag entrainment during continuous casting of steel in billets and slabs.** *The 8th International SteelSim Conference.* 2019.
Publisher Full Text

21. Mier D, Nazim Jalali P, Ramirez Lopez P, *et al.*: **A stochastic model of the process of sequence casting of steel, taking into account imperfect mixing.** *Appl Phys B.* 2019; **125**: 65.
Publisher Full Text

22. Louhenkilpi S: **Continuous casting of steel.** *Treatise on Process Metallurgy.* Vol. 3. Elsevier; 2014; 373–434.
Publisher Full Text

23. Sgrò A, Rinaldi M, Cristallini A, *et al.*: **Optimum nozzle design for beam blanks mould casting.** *ISIJ Int* (special issue - Cutting Edge of Computer Simulation of Solidification, Casting & Refining"). 2014; **54**(3).

24. Ridolfi MR: **Hot tearing modelling: a microstructural approach applied to steel solidification.** *Metall Mater Trans B.* 2014; **45**: 1425–1438.
Publisher Full Text

25. Ridolfi MR: **Effect of the dendritic morphology on hot tearing of carbon steels.** *IOP Conf Ser: Mater Sci Eng.* 2016; **117**(1): 012063.
Publisher Full Text

26. De Santis M, De Santis N, Fera D, *et al.*: **Online tool based on Tundish steel CFD model to monitor and minimise steel intermix in CC slabs.** *MaterTech.* 2019; **107**(5): 510.
Publisher Full Text

27. de Micheli P, *et al.*: *Towards the simulation of the whole manufacturing chain processes with FORGE®. In NEMU 2015 – New Developments in Forging Technology.* Fellbach, Germany; 2015, May.
Reference Source

28. Šarler B, Mavrič B, Dobravec T, *et al.*: **A meshless multiscale and multiphysics slice model for continuous casting of steel.** *Metals.* 2025; **15**(9): 1007.
Publisher Full Text

29. Zhang X, Pirker S, Saeedipour M: **Numerical investigation of particle motion at the steel—slag interface in continuous casting using VOF method and dynamic overset grids.** *Exp Comput Multiph Flow.* 2023; **5**: 178–191.
Publisher Full Text

30. Zhang X, Pirker S, Saeedipour M: **Investigation of inclusion removal at steel–slag interface toward a small-scale criterion for particle separation.** *Steel Res Int.* 2023; **94**(7): 2200842.
Publisher Full Text

31. Zhang X, Michelic S, Pirker S, *et al.*: **Detachment of a soluble particle at the slag-argon interface: CFD study and experimental observations.** *Metall Mater Trans B.* 2024; **55**: 1442–1454.
Publisher Full Text

32. Holzinger G, Zhang X: **Non-metallic inclusion capture at the steel-slag interface in tundish simulations.** *Presented at Liquid Metal Processing Conference.* Leoben, Austria 2024.

33. Michelic S, Bernhard C: **Significance of Nonmetallic Inclusions for the clogging phenomenon in continuous casting of steel - a review.** *Steel Res Int.* 2022; **93**(7): 2200086.
Publisher Full Text

34. Barati H, Wu M, Kharicha A, *et al.*: **A transient model for nozzle clogging.** *Powder Technol.* 2018; **329**: 181–198.
Publisher Full Text

35. Barati H, Wu M, Kharicha A, *et al.*: **Calculation accuracy and efficiency of a transient model for Submerged Entry Nozzle clogging.** *Metall Mater Trans B.* 2019; **50**: 1428–1443.
Publisher Full Text

36. Barati H, Wu M, Kharicha A, *et al.*: **Role of solidification in Submerged Entry Nozzle clogging during continuous casting of steel.** *Steel Res Int.* 2020; **91**(12): 2000230.
Publisher Full Text

37. Barati H, Wu M, Michelic S, *et al.*: **Mathematical modelling of the early stage of clogging of the SEN during continuous casting of Ti-ULC.** *Steel Metall Mater Trans B.* 2021; **52**: 4167–4178.
Publisher Full Text

38. Barati H, Wu M, Kharicha A, *et al.*: **Transient simulation of melt flow, clogging, and clog fragmentation inside SEN during steel continuous casting.** *IOP Conf Ser Mater Sci Eng.* 2023; **1281**: 012025.
Publisher Full Text

39. Barati H, Wu M, Ilie S, *et al.*: **Numerical modelling of clog fragmentation during SEN clogging in steel continuous casting.** *Powder Technol.* 2024; **434**: 119307.
Publisher Full Text

40. Pirker S, Kahrimanovic D, Schneiderbauer S: **Secondary vortex formation in bifurcated Submerged Entry Nozzles: numerical simulation of gas bubble entrapment.** *Met Mat Trans B.* 2015; **46**(2): 953–960.
Publisher Full Text

41. Javurek M, Wincor R: **Bubbly mold flow in continuous casting: comparison of numerical flow simulations with water model measurements.** *Steel Res Int.* 2020; **91**(12): 2000415.
Publisher Full Text

42. Javurek M, Brummayer M, Wincor R: **Turbulent flow measurements in continuous steel casting mold water model.** *Mater Today Proc.* 2022; **62**(5): 2581–2586.
Publisher Full Text

43. Javurek MIlie S: **Simulation of flow-induced inclusion deposition in a continuous casting strand**. In: *6th European Steel Technology and Application Days (ESTAD).* Düsseldorf, Germany, 2023.
Reference Source

44. Gruber C, Barati H, Holzinger G, *et al.*: Success stories of CFD modelling in understanding the continuous casting process: the impact of microscopic dynamics on macroscopic scales. Proceedings of "15th International Conference on Industrial Applications of Computational Fluid Dynamics". Trondheim, Norway, 2024.
Reference Source

45. Panaras GA, Theodorakakos A, Bergeles G: **Three-dimensional modeling of the flow and the interface surface in a continuous casting mold model.** *Metall Mater Trans B.* 1998; **29**(B): 1117–1126.

46. Tscheuschner C, Rödl S: **Numerical simulation of solidification and resulting strains/stresses in the strand shell for asymmetric casting.** *METEC.* 2015.

47. Tscheuschner C, Schäperkötter M, Müller P: **Analysis and optimisation of mould cooling conditions by application of CFD modelling and verification in industrial trials.** *ECCC.* 2017.

48. Schlautmann M, Köster M, Krieger W, *et al.*: **Measurement and model-based control of solidification in continuous casting of steel billets.** *Appl Sci.* 2023; **13**(2): 885.
Publisher Full Text

49. Helmholtz-Zentrum Dresden-Rossendorf (HZDR) WebPage, Liquid Metal Model for Continuous Casting (LIMMCAST).
Reference Source

50. Timmel K, Wondrak T, Eckert S: **Experimental modelling of continuous casting of steel in slab moulds using low melting liquid metals.** *IOP Conference Series: Materials Science and Engineering.* 2018; **424**: 012032.
Publisher Full Text | **Reference Source**

51. Helmholtz Zentrum Dresden Rossendorf (HZDR): *Experimental Facilities.* 2025.
Reference Source

52. Velička M, Pyszko R, Machů M, *et al.*: **Research on solid shell growth during continuous steel casting.** *Materials.* 2023; **16**(15): 5302.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

53. Yang H, Eck J, Ramirez Lopez PE: **Analysis of a full-scale Bi-Sn liquid metal model for the continuous casting of steel.** *Met Mater Int.* 2023; **30**(5): 1–17.
Publisher Full Text

54. Ramirez Lopez PE, Kesavan S, Yang H, *et al.*: **Optimization of casting praxis using swerim's digital twin.** *8th International Congress on the Science and Technology of Steelmaking.* 2022;
Publisher Full Text

55. Yang H, Ramirez Lopez PE, Mier Vasallo D, *et al.*: **Effect of shear-thinning behavior on slag entrapment and mold friction during continuous casting**. *Conference Paper, 10th European Conf. on Continuous Casting.* Bari, Italy, Oct, 2021.
Reference Source

56. Yang H, Ramirez Lopez PE, Mier Vasallo D, *et al.*: **Modelling contact and friction at the mold-strand gap through lubrication and contact indexes.** *Conference Paper, SteelSIM 2021, Virtual Conference.* 2021.
Reference Source

57. Yang H, Ramirez Lopez PE, Mier Vasallo D, *et al.*: **Designing non-newtonian mold powders and optimization of process for continuous casting of billet.** *Steel Res Int.* 2021; **93**(3): 2100379.
Publisher Full Text

58. Yang H, Ramirez Lopez PE, Mier Vasallo D: **New concepts for prediction of friction, taper, and evaluation of powder performance with an advanced 3D numerical model for continuous casting of steel billets.** *Metall Mater Trans B.* 2021; **52**(4): 2760–2785.
Publisher Full Text

59. Yang H, Ramirez Lopez PE, Mier Vasallo D, *et al.*: **Modelling of non-Newtonian mold powders for continuous casting of steel**. *Conference Paper, The 11th Molten Slags, Fluxes and Salts, MOLTEN 2020*. Seoul, Korea May, 2021.
Reference Source

60. Yang H, Kesavan S, Mier Vasallo D, *et al.*: **The influence of thermo-physical properties on slag entrainment during continuous casting of steel in billets and slabs.** *SteelSim 2019.* 2019;
Publisher Full Text

61. Yang H, Kesavan S, Ramirez Lopez PE, *et al.*: **Numerical modelling of the flow field in a bloom caster under the influence of an in-mold electromagnetic stirrer**. *8th International Conference on Modelling and Simulation of Metallurgical Processes in Steelmaking.* Toronto, 2019.
Publisher Full Text

62. Mier Vasallo D, Nazem Jalali P, Ramirez Lopez PE, *et al.*: **A stochastic model of the process of sequence casting of steel, taking into account imperfect mixing.** *Appl Phys B.* 2019; **125**(4): 65.
Publisher Full Text

63. Ramirez Lopez PE, Nazem Jalali P, Sjöström U, *et al.*: **Key lubrication concepts to understand the role of flow, heat transfer and solidification for modelling defect formation during continuous casting.** *ISIJ Int.* 2017; **58**(2): 201–210.
Publisher Full Text

64. Nazem Jalali P, Ramirez Lopez PE, Nilsson C: *Diagnosis and optimisation of continuous casting practices through numerical modelling.* Feb. 2016.
Reference Source

65. Lindwall J, Ramirez Lopez PE, Nazem Jalali P: **One-way coupling of an advanced CFD multi-physics model to FEA for predicting stress-strain in the solidifying shell during continuous casting of steel.** *IOP Conf Ser Mater Sci Eng.* 2015; **84**(1): 012097.
Publisher Full Text

66. Ramirez Lopez PE: *Progress in applied CFD, selected papers from 10th International Conference on Computational Fluid Dynamics in the Oil & Gas Metallurgical and Process Industries*. Olsen JE, Johansen ST, editors. 1 st ed. SINTEF; Jan 2015.
Reference Source

67. Ramirez Lopez PE, Nazem Jalali P, Nilsson C: **Adding argon injection to an advanced model for continuous casting of steel**. *8th European Continuous Casting Conference.* Graz, Austria, Jun, 2014.
Reference Source

68. Ramirez Lopez PE, Björkvall J, Olofsson C, *et al.*: **Continuous casting simulator for measurement and control of liquid metal flow in the mould**. *8th European Continuous Casting Conference - Graz.* Austria, Jun, 2014.
Reference Source

69. Nazem Jalali P, Ramirez Lopez PE, Däcker CÅ, *et al.*: **Analysing the performance of mould powders for niche steels through advanced numerical modelling**. *8th European Cont Casting Conference.* Graz, Austria, Jun, 2014.
Reference Source

70. Ramirez Lopez PE, Nazem Jalali P, Sjöström U, *et al.*: **Adding argon injection through the DPM+VOF technique to an advanced multi-physics and multi-scale model for continuous casting of steel**. *8th European Continuous Casting Conference.* Graz, Austria, 2014.
Reference Source

71. Mills KC, Ramirez Lopez P, Lee PD, *et al.*: **Looking into continuous casting mould.** *Ironmak Steelmak.* 2014; **41**(4): 242–249.
Publisher Full Text

72. Castagne S, Pascon F, Miesse G, *et al.*: *Finite element analysis of continuous steel casting.* 2003.
Reference Source

73. Louhenkilpi S, Miettinen J, Laine J, *et al.*: **Online modelling of heat transfer, solidification and microstructure in continuous casting of steel.** *IOP Conf Ser Mater Sci Eng.* 2019; **529**: 012051.
Publisher Full Text

74. Norrena J, Louhenkilpi S, Visuri V-V, *et al.*: **Coupling of solidification and heat transfer simulations with interpretable machine learning algorithms to predict transverse cracks in continuous casting of steel.** *Steel Res Int.* 2024; **95**(4): 2300529.

75. Louhenkilpi S, Miettinen J, Visuri V-V, *et al.*: **Application of the IDS solidification and microstructure tool for quality prediction in continuous casting of steel with novel phenomenological quality criteria**. *In Proceedings of the 10th European Conference on Continuous Casting.* 2021.

76.
Reference Source

77. Ludwig O, Aloe M, Thevoz P: State of the art in modelling of continuous casting. Calcom ESI SA; n.d.
Reference Source

78. Xia C-H, Wang K, Song X, *et al.*: **Overview of multi-scale simulation techniques for three typical steel manufacturing processes.** *Materials.* 2024; **17**: 3173.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

79. Thomas BG: *Computational modeling of flow, heat transfer, and deformation in the continuous casting of steel. In 1st Baosteel Annual Academic Conference, May 27–28.* 2006; Shanghai, China.

80. Natterer ES, Rao SR, Lapuerta AT, *et al.*: **Machine learning surrogates for agent-based models in transportation policy analysis.** *Transp Res C-Emerg Technol.* 2025; **180**: 105360.
Publisher Full Text

Open Peer Review

Current Peer Review Status: ✗ ? ?

Version 1

Reviewer Report 27 December 2025

https://doi.org/10.21956/openreseurope.22716.r64231

© **2025 Mu W.** This is an open access peer review report distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The author(s) is/are employees of the US Government and therefore domestic copyright protection in USA does not apply to this work. The work may be protected under the copyright laws of other jurisdictions when used in those jurisdictions.

?

Wangzhong Mu
[1] Engineering Materials, Lulea University of Technology Department of Engineering Sciences and Mathematics (Ringgold ID: 407846), Luleå, Norrbotten County, Sweden
[2] Engineering Materials, Lulea University of Technology Department of Engineering Sciences and Mathematics (Ringgold ID: 407846), Luleå, Norrbotten County, Sweden

In general, this is a very good overview to summarize the continuous casting simulation, one of the vital research areas in metallurgy. This work more focus on the survey of the model expertise development in different European universities and research institutes. According to the reviewer, there is not much review article highlighting this point, in this case this review article is worth being published after revision.

The reviewer can understand this is not a critical review focusing on the research aspect of continuous casting simulation, but more for an overview and summary of different European affiliations' activity. It is more suggested to add more search contents, for instance, each university/institute can introduce 1-2 representative research results/achievements (Figures or Tables can be a better way), which could attract the audience more, and this will also let the readers know each party's expertise.

Furthermore, this overview article includes many aspects of continuous casting modelling, but also some bullets are not covered. For instance, the modelling/simulation here means the numerical simulation, but there are also some important experimental simulation research activities that are rather important for continuous casting, .e.g. Mold Crack Simulator (MCS), Single/Double Hot Thermocouple Technique (SHTT/DBTT), High-Temperature Confocal Laser Scanning Microscopy (HT-CLSM), etc. which use to simulate different phenomenon of dendrite formation, crystallization of mold flux, non-metallic inclusion motion behavior during casting, etc. These items could be possibly mentioned at the beginning of the report.

Besides, for the numerical simulation, there are some state-of-the-art techniques which could also

be mentioned. For example, CALPHAD (CALculation of PHAse Diagrams) is coupling with the CFD simulation to use in some solidification/casting research; AI-based branches, e.g. machine learning, are used to predict the solidification microstructure, and defects (cracks, macro segregation, porosity, inclusion, etc.) for the quality control of casting lab, etc. These research directions could be included either in the beginning or the end of the report.

Last but not least, there are some details maybe the authors can consider improving. For example, Figure 2 gives a mapping of world skill in casting modelling, it is suggested to provide the quantitative analysis how to judge this skill level. Figure 4 starts in 2013, and actually there are quite some good work done by different EU projects which can be considered to expand this figure content.

Is the topic of the review discussed comprehensively in the context of the current literature?
Yes

Are all factual statements correct and adequately supported by citations?
Yes

Is the review written in accessible language?
Yes

Are the conclusions drawn appropriate in the context of the current research literature?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Steelmaking, continuous casting, sustainable metallurgy, experimental characterization, alloy design

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 24 December 2025

https://doi.org/10.21956/openreseurope.22716.r64233

© 2025 Dou K. This is an open access peer review report distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

?

Kun Dou
[1] Central South University, Changsha, China
[2] Central South University, Changsha, China

This manuscript attempts to provide a thematic and geographic mapping of European expertise in continuous casting (CC) modeling. While the topic is relevant and the effort to consolidate scattered knowledge is commendable, the manuscript in its current form lacks the scientific rigor, critical depth, and structural coherence expected for a review article. It reads more like a project report or a directory listing rather than a comprehensive scholarly synthesis. Major revisions are required to elevate it to an acceptable academic standard.

The manuscript has potential but requires substantial revisions to meet scholarly standards. By addressing the gaps in critical analysis, expanding the scope of institutions and literature, and refining the structure, the authors can transform this into a valuable reference for the CC community. **I** encourage a resubmission after major revisions.

References

1. Xia C, Wang K, Song X, Pan W, et al.: Overview of Multi-Scale Simulation Techniques for Three Typical Steel Manufacturing Processes. *Materials*. 2024; **17** (13). Publisher Full Text

Is the topic of the review discussed comprehensively in the context of the current literature?

Yes

Are all factual statements correct and adequately supported by citations?

Yes

Is the review written in accessible language?

Yes

Are the conclusions drawn appropriate in the context of the current research literature?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Casting and solidification of metals and alloys, numerical modelling, machine learning, ICME

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 25 September 2025

https://doi.org/10.21956/openreseurope.22716.r59017

© 2025 Schwarze R. This is an open access peer review report distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Rüdiger Schwarze
[1] TU Bergakademie Freiberg, Freiberg, Germany
[2] TU Bergakademie Freiberg, Freiberg, Germany

The submitted manuscript exhibits significant scientific shortcomings that substantially undermine its quality and academic relevance, rendering a positive evaluation impossible.

First and foremost, the scientific approaches underlying the manuscript are not discernible. There is no critical discourse, no well-defined research question, and no clear scientific framework. Instead, the paper presents a mere enumeration of simulation methods and tools—without any explanation of their physical foundations, application domains, or limitations. This bullet-point-style listing reads more like a technical product catalog than a scholarly contribution.

I expected the manuscript to provide a comprehensive overview of the current state of research in continuous casting, particularly highlighting recent European research trends. Instead, the paper lacks a thorough literature review and fails to engage with contemporary developments, key challenges, or methodological innovations. Notably, the growing use of machine learning—a central trend in modern materials science and process optimization—is mentioned only superficially, without any discussion of its relevance, application potential, or limitations. This superficial treatment of current research trends suggests that the manuscript is not grounded in a rigorous engagement with the existing literature.

The selection and presentation of research institutions deemed "leading" by the authors are particularly problematic. This selection is made without any transparent or justifiable criteria. No evaluation framework or selection process is provided, making the list appear arbitrary to the reader. Several internationally recognized and influential research institutions—prominent in the field of continuous casting—are entirely omitted. Most notably, the state-of-the-art liquid metal model casting facilities at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR), which are globally acknowledged as reference installations, are not mentioned at all—an omission that severely compromises the credibility of the selection.

Furthermore, the descriptions of the selected institutions are inadequate: they are presented exclusively in bullet points and resemble promotional material rather than a substantive, scientific analysis. The claimed "outstanding competencies" of these institutes remain vague and are not substantiated.

Given these serious deficiencies—lack of scientific depth, superficial literature engagement, arbitrary selection of institutions, absence of critical analysis, and weak scientific argumentation—the manuscript is fundamentally flawed. Even a revision appears insufficient, as the core issues lie in the manuscript's scientific approach and overall structure.

Recommendation: Due to the numerous and profound shortcomings, of the manuscript I recommend not approved in its current form.

Is the topic of the review discussed comprehensively in the context of the current literature?

No

Are all factual statements correct and adequately supported by citations?
No

Is the review written in accessible language?
Partly

Are the conclusions drawn appropriate in the context of the current research literature?
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: fluid dynamics, numerical and experimental modeling, material science

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Comments on this article

Version 1

Author Response 10 Mar 2026

Michele DE SANTIS

The revised text attached aims to integrate all suggestions raised by the reviewers after the first version of the manuscript. Details are reported in the track change form, together with detailed correspondence between modifications and remarks from each reviewer. In general, the new version provides, first : a) additional details on several technical aspects (including the addition of a dedicated paragraph on AI); b) incorporates references to European papers; and c) clarifies that the list of research centers presented is not exhaustive, while nonetheless highlighting the main contributions of those included (with appropriate referencing) Finally—and most importantly—the criteria used for the geographical classification of skills in the modelling of steel casting are now more explicitly described. Hoping now the paper is more adquate for publications, and, on behalf of all Authors, grateful for the time and consideration you have devoted to evaluating our work, kind regards, Michele De Santis

Competing Interests: No competing interests were disclosed.

Reader Comment 28 Nov 2025

Wangzhong Mu, Lulea University of Technology Department of Engineering Sciences and Mathematics, Luleå, Sweden

First of all, it is a very good overview of this research area (e.g. casting model, etc.), but can we

more specify the comparison the state of the art of this area at Europe, and the rest of the world?

Competing Interests: n/a