



D8.3 Report on Sensors Design

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Abstract

Deliverable D8.3 presents the outcomes of Task 8.3, which focuses on the design and preparation of three novel sensor systems to enhance data availability in the continuous casting process. The objective of the task is to define, specify, and prepare the deployment of advanced monitoring solutions that provide reliable, real-time information required by ProcTwin project. The work includes the assessment of industrial constraints, collaborative definition of requirements together with GSW, and the development of sensor concepts adapted to the harsh operating conditions of steel manufacturing.

The deliverable summarizes the design of the three systems: a surface-quality inspection camera for detecting defects on hot billets, a mould-powder monitoring system for observing powder coverage in the mould, and a fibre-optic temperature measurement system for distributed thermal monitoring inside the mould walls. For each sensor, the document outlines its purpose, configuration, installation principles, and the expected benefits for process understanding.

Together, these systems represent a significant step toward increasing process transparency and supporting the predictive capabilities of ProcTwin's digital twin framework. By providing structured and high-quality data on surface condition, mould powder behaviour, and temperature distribution, they will enable more accurate modelling, improved control strategies, and overall higher product quality. The deliverable thus offers a clear and accessible overview of the achieved technical progress for both technical and non-technical audiences.

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Glossary

Abbreviation	Meaning
JSON	JavaScript Object Notation
VIS	Visual (wavelength range)
NIR	Near InfraRed (wavelength range)
IR	InfraRed (wavelength range)

1. Introduction

The purpose of this deliverable is to present the design and preparation activities carried out in Task 8.3 of the ProcTwin project, which focuses on developing advanced sensor systems to enhance monitoring capabilities in continuous casting. Reliable and high-quality process data is a fundamental requirement for the digital twin framework that ProcTwin aims to establish. In this context, Task 8.3 concentrates on defining, specifying, and preparing three complementary sensor solutions that will provide essential real-time measurements related to billet surface quality, mould powder behaviour, and mould temperature distribution.

The deliverable describes the collaborative work performed by CARTIF, BFI, ISEND and GSW, including the identification of industrial requirements, analysis of boundary conditions, and the evaluation of feasible technical options. It provides an overview of the selected sensor concepts and summarizes their expected contribution to improved process understanding, quality control, and future digital twin integration. The document is written for a general audience and presents the results in an accessible and non-technical way, in line with the public dissemination level of this deliverable.

1.1 Scope

The scope of this deliverable is limited to the design and specification phase of the three sensors developed under Task 8.3. It covers the definition of measurement needs, the analysis of installation constraints, and the selection of the most suitable sensing technologies for the industrial environment of GSW's continuous casting machine. The document includes the conceptual design of each sensor system, the preliminary engineering considerations, and the first evaluation of how the generated data will be structured and exchanged with plant systems.

1.2 Deliverable role within the project

D8.3 plays a central role in WP8 by establishing the technical baseline for the sensor systems that will feed the ProcTwin project. The deliverable consolidates the results of requirement-gathering activities, plant visits, partner consultations and preliminary laboratory work. It ensures that all three sensors - mould powder monitoring camera system, fibre-optic temperature measurement system, and surface inspection camera system - are consistently defined in terms of purpose, configuration, environmental protection, communication interfaces, and integration needs.

By providing these inputs, D8.3 ensures that the monitoring layer of the project is technically mature and ready for the transition towards prototyping and deployment in WP9.

1.3 Outline

The document is structured to guide through the design activities performed in Task 8.3. It begins with an overview of the task objectives and the methodological approach adopted by the partners, followed by a description of the industrial context at GSW and the resulting measurement needs that determine the sensor requirements. The subsequent sections present the detailed design of each of the three sensor systems: the mould powder monitoring system, the fibre-optic temperature measurement system, and the surface quality inspection camera system, including their configuration, installation concepts, and data exchange principles. The deliverable concludes with a summary of the main findings and the planned next steps.

2. Objectives and Methodological Approach -

The main objective of Task 8.3 within Work Package 8 is to design, specify and prepare the installation of three advanced monitoring solutions that will significantly enhance the observability of the continuous casting process at GSW. These sensors constitute essential data sources for the ProcTwin project, which relies on accurate, structured and high-resolution measurements to model thermal behaviour, detect anomalies and predict quality-relevant events along the billet production chain. The systems developed in this task namely the mould powder inspection camera (BFI), the fibre-optic temperature monitoring system for the mould (BFI), and the surface quality inspection camera system (CARTIF–ISEND) represent a coordinated and complementary approach to addressing critical gaps in process information that currently limit advanced process control and prediction.

The objectives of Task 8.3 can be categorised into three main domains.

First, technical definition and specification, which includes identifying measurable quantities relevant to quality and process stability, selecting the most appropriate sensing technologies, analysing the environmental and integration constraints of the GSW casting machine, and preparing a technical design suitable for deployment under industrial conditions.

Second, methodological alignment with WP8 and the broader ProcTwin architecture, ensuring that each sensor contributes coherent, interoperable and well-structured data flows to the project's digital infrastructure.

Third, coordinated validation and preparation for installation, guaranteeing that all three systems follow a harmonised engineering approach, facilitating later commissioning, testing, and connection to the process-level models developed in other work packages.

The methodology adopted for this task followed a multi-stage, collaborative and iterative process led jointly by CARTIF and BFI, with essential operational and contextual support from GSW and complementary expertise from ISEND and SWERIM. The first phase consisted of requirement gathering, including several technical meetings, on-site visits, and direct assessment of the casting machine layout, mould configuration and existing data-acquisition systems. During visits to GSW, partners inspected the mould area, tundish region, cooling zones and surface-inspection sections of the casting line. This allowed the team to identify visibility constraints, thermal exposure levels, accessibility restrictions, and potential integration points for cabling, mechanical supports and protective housings. Early exchange of drawings, videos and photos from GSW provided the necessary dimensional references for drafting sensor layouts and determining minimum installation distances, limits for optical paths, and requirements for cabling routes.

The second phase addressed conceptual design and evaluation of sensing principles. BFI conducted a systematic assessment of technologies available for mould monitoring, and solutions for distributed temperature measurement. CARTIF and ISEND carried out optical simulations, feasibility studies and initial image-processing tests to assess the detectability of surface defects under hot-steel illumination conditions. During this stage, alternative configurations were evaluated with respect to robustness, reliability, expected data quality, ease of calibration, and long-term maintainability. Selection criteria included spectral response, dynamic range, acquisition frequency, temperature tolerance, mechanical footprint, and compatibility with industrial enclosure systems.

In the third phase, the partners jointly developed integration strategies, aligning sensor outputs with the data-acquisition architecture of WP8. This included defining standardised data structures, identifying relevant communication protocols, assessing cybersecurity requirements, and ensuring compatibility with the interoperability framework. BFI's experience with Level 2 data integration at steel plants supported the definition of communication schemes for the two mould-area sensors, while CARTIF and ISEND provided specifications for transferring processed images and defect indicators

into supervisory systems. The methodological approach emphasised modularity, allowing each sensor to operate autonomously while also contributing to a common data repository accessible for modelling, prediction, and future operator-support tools.

Overall, the methodological approach of Task 8.3 ensured that the proposed sensors are technically sound, operationally feasible and fully aligned with the broader ProcTwin architecture. By combining industrial experience, academic expertise and technology-provider know-how, the partners have established a solid foundation for the subsequent prototyping, installation and commissioning phases. The designs produced in this task represent an important milestone in enabling advanced monitoring and predictive capabilities for continuous casting and, more broadly, supporting the integrated digital twin strategy of the project.

3. Industrial Context and Measurement Needs

Global Steel Wire (GSW) in the Celsa Group in Spain produces long steel products. Within ProcTwin project, the production steps in focus are continuous casting, walking beam reheating, hot wire rolling, and quality inspection, but data from previous process steps will be integrated too, thus covering the complete chain. The monitoring system for quality-critical continuous casting process, developed within the project, utilizes advanced sensors (Figure 1) and physics models to anticipate and prevent quality issues in final products, thereby enhancing production efficiency and reducing scrap production.

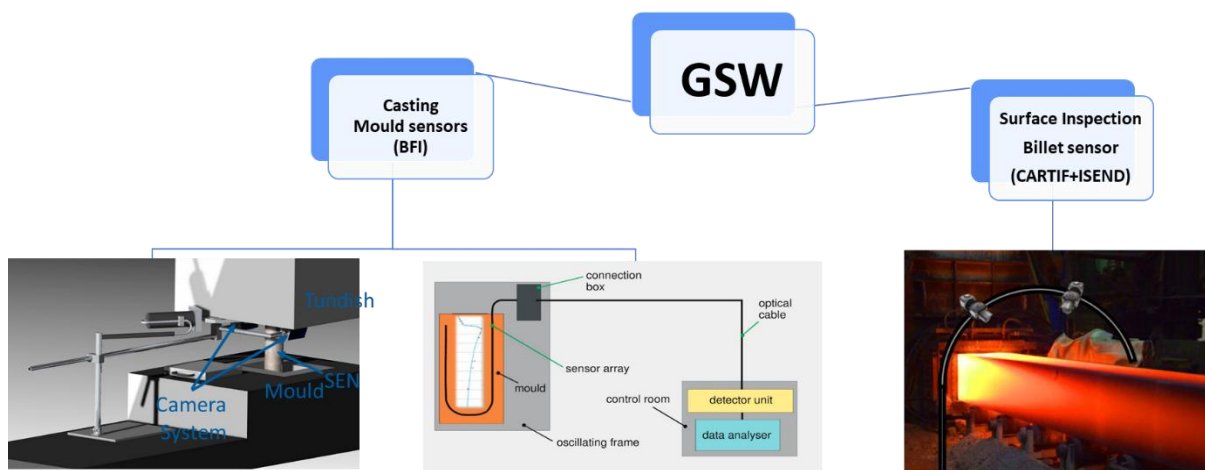


Figure 1: Measurement systems developed and tested in ProcTwin project at GSW

Casting is a critical step in steel production, where molten steel is solidified into semi-finished shapes for further processing. The production process at GSW involves:

- **Melting and Refining:** Steel is melted in an electric arc furnace (EAF) and refined in secondary metallurgy to achieve the desired chemical composition and casting temperature.
- **Pouring:** The molten steel is poured from the steelmaking ladle into a tundish, and then through continuous casting machine.
- **Continuous Casting:** GSW uses continuous casting, where steel flows through a water-cooled mould and solidifies while moving along the 6 lines available.
- **Solidification:** The steel cools and solidifies into billets.
- **Cutting and Cooling:** The solidified steel is cut to length and cooled before further rolling or finishing.

The occurrence of defects in steel (semi-)products is strongly dependent on the conditions of the continuous casting process, in particular the initial solidification in the mould, which therefore has a big impact on the amount of rework and recycling required, and the resource efficiency of the steel production in general. On the other hand, the casting process is characterized by a harsh environment (liquid steel enters casting process with $\sim 1500-1600\text{ }^{\circ}\text{C}$) and inaccessibility of important features by traditional sensor systems. A mould powder monitoring system (VIS/IR) and fibre optical temperature sensors (FOTS) will be applied in this project to enable a better monitoring of the casting process and to enlarge the data basis for the modelling and data analysis.

Metallurgical quality in the casting process can be enhanced by sensorization over some or all systems of the caster. Installing new solutions with camera analysis will provide a higher level of quality,

detecting the defects in the first stages of the production process. At the chosen sensing location for the project, in the metallurgical length of the continuous casting (before cutting), the steel is at a very high temperature, above 1000°C. Capturing images in the visible spectrum under these conditions presents two major problems that have to be overcome. On the one hand, the heat emitted that affects the camera materials, including lenses, housings, cables, filters, etc., can damage them, so they must be properly protected. On the other hand, an object at high temperature emits radiation, and its emission peak shifts as the temperature varies, according to Wien's displacement law, being located in the red zone for steel at the temperature of the chosen location. The amount of energy received in the visible spectrum is significant enough to influence the measurement of the cameras, so steps will be taken to correct it and isolate it from the signal of the light source we use to reveal the defects.

The atmospheric conditions in the melt shop environment are generally characterized by extremely high temperatures, high relative humidity, and the presence of various atmospheric pollutants, including fine particles. This demanding environment presents a significant challenge for the reliable operation of sensitive electronic equipment.

Thus, the following measurement requirements are defined for the different systems:

Table 1: Sensors environment requirements

	Mould powder monitoring	FOTS	Hot surface inspection
High temperature resistance	x (adequate protection)	x (suitable sensors)	x (adequate protection)
No impact on production operators	x		x
Not influence cooling water flow in mould		x	
Mechanical robustness	x (e.g. tundish change)	x (e.g. mould change)	x
Dust robustness	x		x
Humidity robustness			x
Adequate resolution	x	x	x
Adequate data frequency	x	x	x

4. Camera System for Mould Powder Inspection

4.1 Introduction

During the casting process, the steel surface in the mould is covered by a powder layer that is very important to steel quality. The mould powder is added periodically, either automatically (at GSW) or manually. The powder sinters and melts to form a protective layer, which helps to capture impurities and inclusions and to avoid re-oxidation. The liquid layer of the mould powder is affected by the flow of the steel and drawn into a gap between the steel shell and the mould. There it acts as a lubricant and contributes to more even heat transfer.

To ensure a closed layer of mould powder on the steel surface, a mould powder monitoring system using NIR and later IR sensors were developed and tested at billet and slab casting machines in previous research projects. It can detect the mould powder break-up prior than visible inspection by the operators and allows a continuous online monitoring and data storage. In ProcTwin, the implementation of a mould powder monitoring system will contribute to the approach for integrating advanced monitoring systems to collect real-time data on process conditions, energy consumption, and product quality. The project employs predictive analytics models to forecast energy consumption and product quality, enabling proactive decision-making to optimize process parameters.

4.2 System overview

The mould powder surface will be supervised by a system composed of a monitoring system and an image analysis system (see Figure 2). The monitoring system includes two cameras with IR sensor to monitor the thermal radiation of the mould powder surface and a protective housing to protect the cameras against harsh environment. The system will be adapted to the local conditions in the plant to monitor as much of the mould surface as possible and to protect the sensor from high temperatures, heat radiation and dust. The image analysis system acquires the images from the cameras, analyses the images, extracts important information (e.g. starting point, frequency and intensity of mould powder break-up), displays the results on a screen and transfers the results to the project database. It will also be adapted to the local conditions (correct definition of ROI, parameter adaption, ...). Besides the two main components there will be a supply of data transfer, power to cameras and cooling gas (or water).

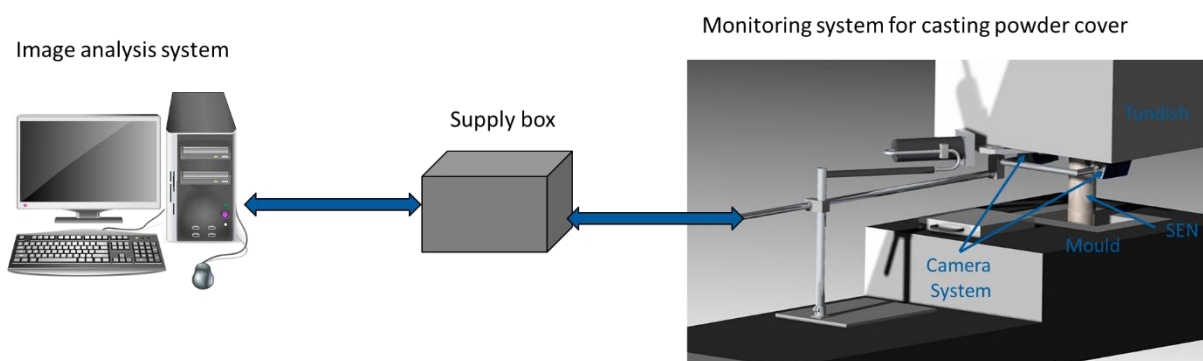


Figure 2: Sketch of mould powder coverage inspection.

4.3 Camera configuration

To select a suitable camera, a research was made regarding available cameras on the market. The following criteria were used to evaluate the cameras (see also Figure 3):

- Spectral range,
- Resolution,
- Frame rate,
- Temperature measurement range,
- Minimum working distance and availability of variable objectives,
- Field of view,
- Dimensions of the camera,
- Maximum operating temperature,
- Interface, and
- Price of camera.

	Flir AX8	Flir BOSON 320	InfraTec PIR uc 180	irPOD TC160	irPOD TC388	optris Xi80 LT ETH	optris Xi400LT USB
Spectral range [µm]	VIS and 7,5-13	7,5-13	7,5-13	8-14	8-14	8-14	7,5-13
Resolution [Pixel]	640x480 and 80x60	320x256	160x120	160x120	384x288	80x80	382x288
Frame rate [Hz]	9	9	100	50/60	50	50	80
T measurement range [°C]	-10 to 150	n.s.	-20 to 250	n.s.	n.s.	-20 to 900	-20 to 1500 °C
Minimum working distance [m]/ variable objectives	0,2 / no	n.s. / yes	0,1 or 0,5 * / yes	0,13 or 0,3 etc. * / yes	n.s.	n.s. / yes	n.s. / yes
Field of view [°]	48x37	n.s.	dep. on objective	dep. on objective	n.s.	n.s.	n.s.
Dimensions [mm]	54x25x95	21x21x11	51x51x65	48,5x49x50 plus objective	35,5x44,5x44,5	36x90 **	36x100**
max. operating temperatur [°C]	50	80	50	50	60	50	50
Interface	Ethernet	USB 2	USB 2	BNC, LVDS	BNC, LVDS	USB; GigE (PoE)	USB
Price [€]	-1.100	from -2.100	n.s.	- 2.000	-2.100	from 940 ***	1950 ***

optris Xi410 LT ETH	Xi 640 LT USB	Optid Xi 05M ETH	Optid Xi 05M ETH	optris PI200	PI 160	Teledyne DALSA Calibir
8 – 14 µm	8 – 14 µm	500 – 540 nm	500 – 540 nm	VIS and 7,5-13	8,0-14	8-14
382x288	640x480	396x300	396x300	640x480 und 160x120	160x120	320x240
25	32	20	20	32 und 128	120	30
-20 to 1500 °C	-20 to 900 °C	950-2450 °C	450-1800 °C	-20 to 900	-20 to 1500	-25 to 125
				n.s. / yes	n.s. / yes	1 or more * / yes
		14x10	14x10	54x40 and dep. on objective	n.s.	dep. on objective
		36x112-127***	36x112-127***	45x45x62	45x45x60-70**	29x51x29
		50	50	50	-40 - 70	50
GigE	USB	USB; GigE (PoE)	USB; GigE (PoE)	USB 2	USB; GigE (PoE)	GigE
2450	5800	2900	2450	from 3.300	2690 ***	-10.000

Figure 3: Assessment of cameras for mould powder monitoring system.

Based on this assessment, the Flir AX8 camera was chosen with the following specifications:

- Spectral range: VIS and IR (7,5-13 µm),
- Resolution: 640*480 pixel for VIS image, 80*60 pixels fir IR image,
- Frame rate: 9 Hz,
- Temperature measurement range: -10 to 150 °C,
- Minimum working distance/availability of variable objectives: 0,2 m/no,
- Field of view: 48*37 °,
- Dimensions of the camera: 54*25*95 mm,
- Maximum operating temperature: 50 °C, and
- Interface: Ethernet.

4.4 Installation layout

To monitor the surface of the mould and thus the mould powder coverage, the following challenges regarding the field of view are present at the GSW plant:

- Small mould with a relatively high rim,
- Small distance between mould surface and tundish bottom,
- SEN blocking the view to parts of the surface, and
- Powder feeding system blocking the view to parts of the surface.

Thus, two cameras will be placed above the mould surface to enable a view to as much surface as possible. The cameras should be placed as far as possible straight above the mould, avoiding a loss of information due to covering by the rim.

Two installation possibilities exist (Figure 4):

- Hanging the cameras to the tundish, enabling a quick attachment and removal during tundish change,
- Using a tripod which is not disturbing operators and tundish change.

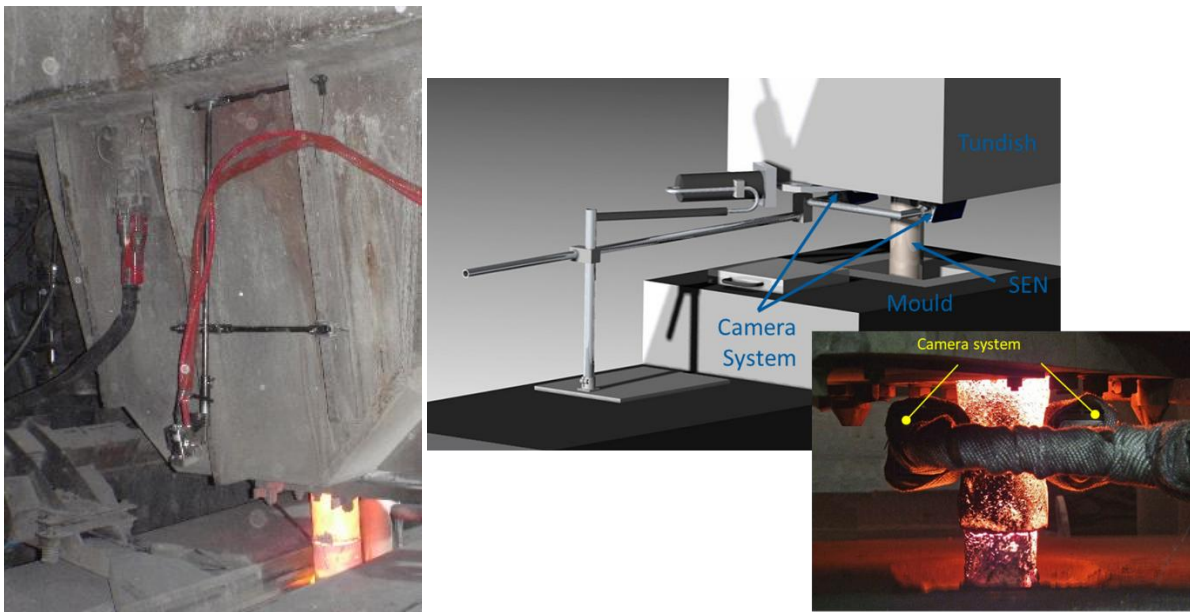


Figure 4: Camera system hanging at tundish (left) and on a tripod (right)

The hanging system allows an easier installation but needs to be removed from the old tundish and attached to the new tundish when tundishes are changed. The challenge is that tundishes can have different layouts, and the position as well as field of view of the cameras should remain as stable as possible for the monitoring. Here, the tripod has the advantage to provide the same view to the surface, but it needs more space and thus could disturb the operators and the tundish exchange. GSW will most likely use the tripod option for mounting the cameras.

4.5 Environmental and safety conditions

The environment where the cameras will be placed (between mould and tundish) is characterized by high temperature and dust appearance.

For protection of the camera, the system will include:

- Thermal insulation and gas cooling for camera and cabling,
- If necessary, shielding plates to protect the cameras from thermal radiation from the SEN,
- If necessary, gas curtain protection for dust protection.

During a first trial on site, the camera temperature and dust collection on the camera objective will be closely monitored, to define if additional measures for protection will be necessary.

4.6 Software development and data transfer

BFI developed a software for monitoring the mould surface to adapt it to the application requirements at GSW. The software enables the operator to acquire and store camera images as well as image analysis results, and visualize it online together with other parameters like camera temperature. Furthermore, the acquired data is transferred to the industrial Edge that is developed at present.

Figure 5 shows an exemplary version of the graphical user interface (GUI) (from a previous project). This displays both camera images and their region of interest (area analysed by the software). Information extracted via image analysis such as the size of the open area (where no mould powder or only a very thin layer is covering the steel surface) and about the sensors are visualised (right and below of camera images), additionally using a warning system that automatically identifies insufficient mould powder coverage and instantly informs the operator via optical traffic light signals.

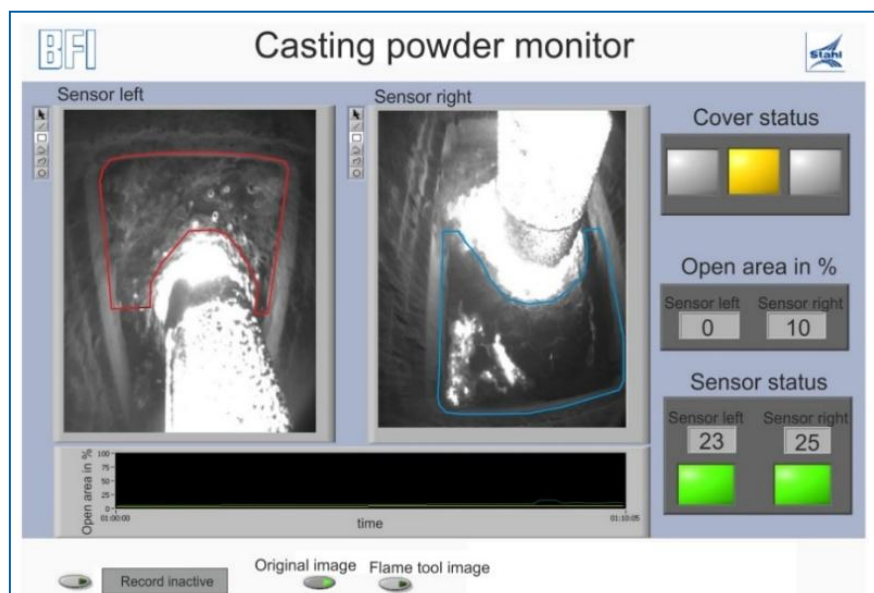


Figure 5: Exemplary GUI (RFCS project Transient, RFSR-CT-2009-00005)

4.7 Conclusion

The mould powder monitoring system has been designed, combining suitable cameras, robust and at the same time flexible mechanical installation as well as suitable data transfer solutions. Thus, it is one of the novel sensors in the quality-critical mould area of the continuous casting machine, which will be combined with a digital twin. The combination of these tools will be a leap forward in the monitoring and control of this process.

The next steps will be a set-up of the camera system at laboratory to implement the image transfer from cameras to BFI software (BFI), preparation of the mechanical components (BFI for camera housing, GSW for holding system), and then a first trial on site (BFI+GSW).

5. Fibre-Optic Temperature Measurement System

5.1 Introduction

To increase the product quality in terms of avoiding cracks, surface defects and geometric deformations, a homogeneous temperature distribution and even shell growth in the mould are fundamental. To fulfil this task, an innovative temperature measurement system with fibre optical temperature sensors (FOTS) will be applied to three moulds of a continuous caster of GSW.

Temperature measurements with fibre optical sensors are carried out using Fibre Bragg Gratings (FBG). With this measuring principle, it is possible to implement up to 20 measuring points on a single fibre. Since the measurement positions can be distributed arbitrarily in every fibre, they can be placed especially in areas of higher interest (e.g. meniscus area and corners). The fibre optic temperature measurement system has many advantages over competing thermocouple-based systems including:

- Increased spatial resolution from dm to mm levels due to an increased number of measurement points on a fibre
- No influence of electromagnetic fields.
- Flexibility of the optical fibre, which allows measurements in places inaccessible for thermocouples.
- Parallel monitoring of multiple fibres for higher resolution and redundancy.
- Minimal influence on mould cooling characteristics.

5.2 System overview

The basic structure of a fibre-optic temperature measurement system essentially consists of the sensor fibres with imbedded local temperature sensor, a detector unit, and a computing unit for data analysis, evaluation and visualisation. For proper operational and task-specific design, it was necessary to extend the basic concept with a pressure- and watertight feed through in the water jacket as well as an industrial-grade flexible cable connection, as shown in Figure 6. Two industrial connectors are foreseen for implementation, one on the mould frame and the other approximately 11 m along the fibre optical cable under the casting platform. In this way, the system can be easily and safely disconnected if maintenance work is necessary or an emergency should occur.

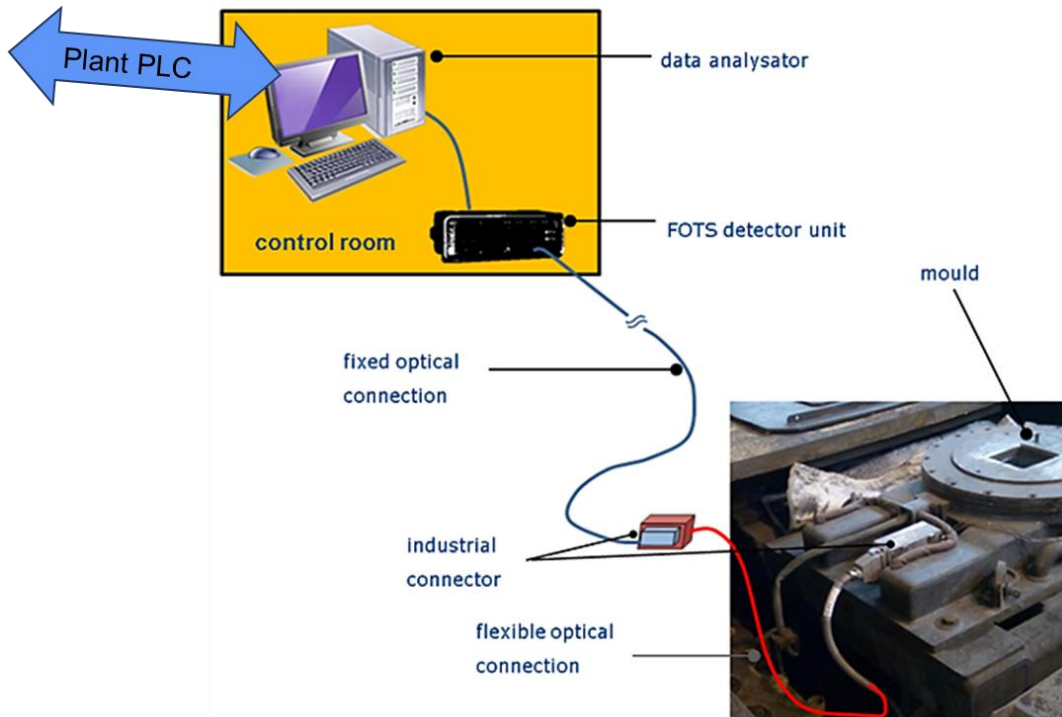


Figure 6 Conceptual design of the fibre optic temperature measurement system.

5.3 Cabling

Due to the harsh and almost inaccessible environment around the mould, it is necessary to design a specific and extensive cable routing for the caster at GSW. Four sensor cables will be routed from the upper part of the mould through the gap for the cooling water flow and then routed through a waterproofed port in the wall of the inner cartridge. Outside the mould support, the cables will then be routed to the connector box on the mould support (see Figure 7).

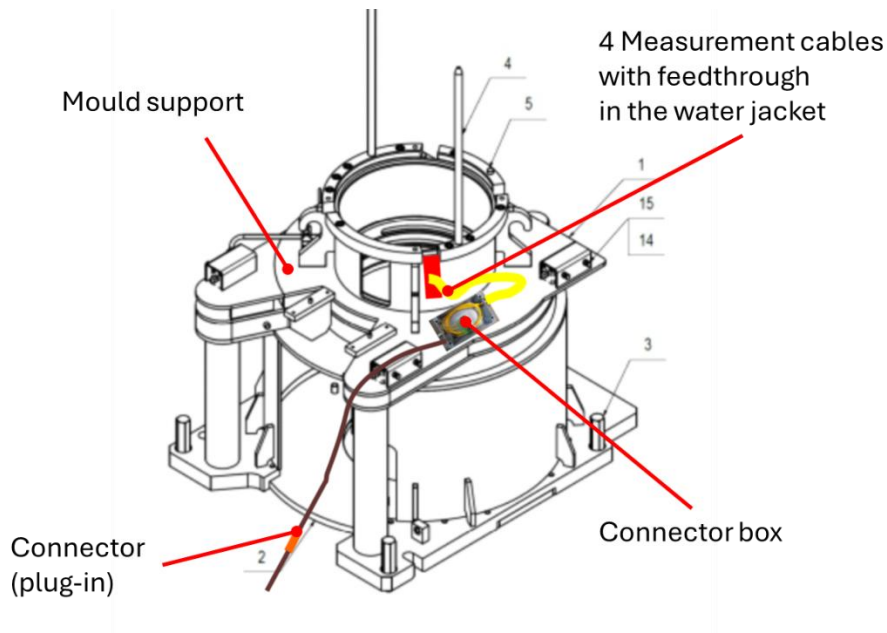


Figure 7 Schematic illustration of FOTS cabling at mould support.

As a plug system, an optical lens connector for harsh industrial environments will be used. This is a necessary adaptation of the system to prevent signal losses since the environment at the caster is rough. In case of the connector on the mould frame, an industrial-grade box to which the measuring fibres are routed is foreseen (Figure 8). For the second connector under the casting platform, a simple plug-in design will be used. The measurement signal will be then transmitted via a fixed optical connection cable to the analyser in the control room.

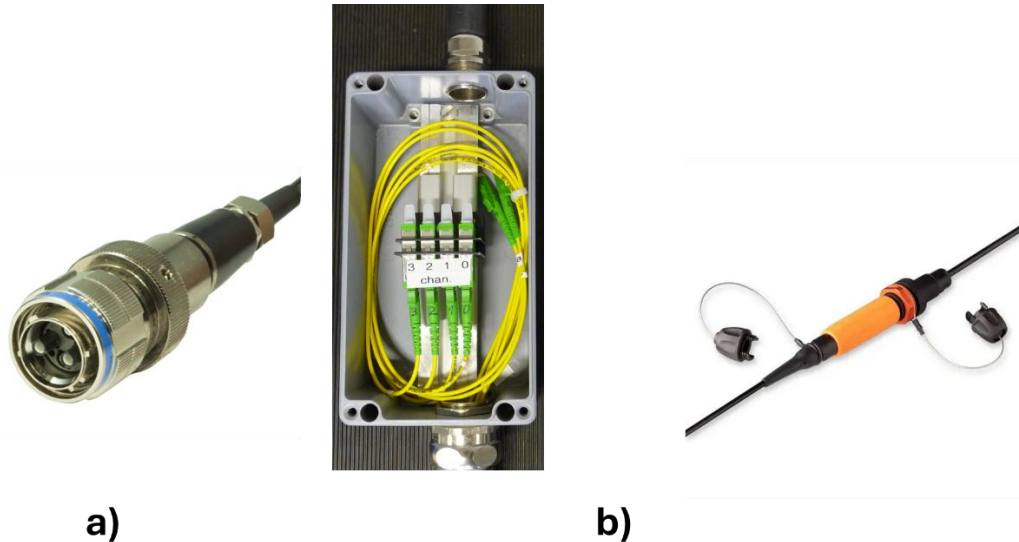


Figure 8 Connector solutions for FOTS implementation at GSW: a) Connector box on mould frame with optical lens plug. b) Plug-in system connector under casting platform.

5.4 Mould design and sensor layout

In discussions between BFI and GSW, it was decided to use the following 4-channel layout for the fibre optic implementation of the temperature sensors in the mould walls (Figure 9). Every channel consists of one measurement fibre with 20 embedded FOTS, so in total 80 temperature measurement points were arranged on one mould.

The fibres are positioned to create a total of 3 horizontal along the circumference and a vertical measurement strand on one mould face. They are distributed in such a way to enable the measurement of local temperatures at multiple positions in casting direction and horizontally, with focus on temperature homogeneity at the 4 faces and temperature gradients in the corner areas of the mould. As indicated in Figure 9 for the vertical measurement strand (fibre 4) the single sensors were placed for a high measurement resolution at the meniscus area (10 mm between sensors) and at the electromagnetic stirrer (20 mm between sensors). In case of the horizontal measurement strands, respectively fibres 1 – 3, (see Figure 10) the sensors are evenly distributed with 5 sensors on every face and a distance of 41 mm.

To ensure the sensor fibres are primarily suitable for temperature measurements and are not influenced by mechanical forces, they are inserted into a copper capillary tube, which also serves as protection (e.g. during system implementation or extraction at the mould shop). The encased sensor fibres are then installed in grooves milled into the outer walls of the mould and are bonded with special high-temperature silicone to allow for easy removal of the system when the mould must be replaced.

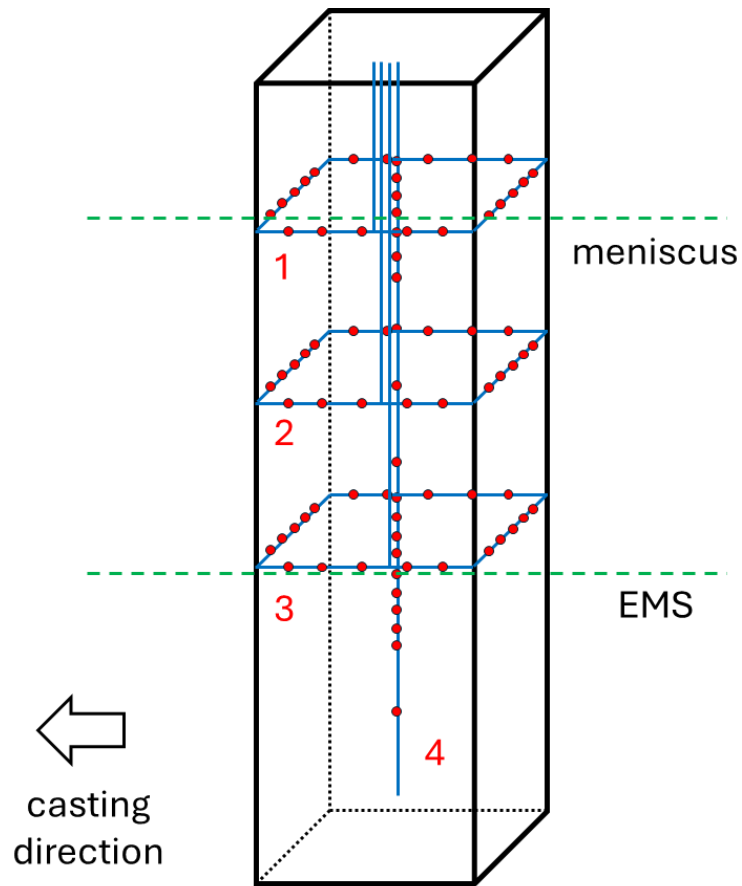


Figure 9 Fibre optical sensor alignment for GSW mould. 3D-view of fibre placement (blue lines) and sensor distribution (red dots) in reference to the casting direction during bending.

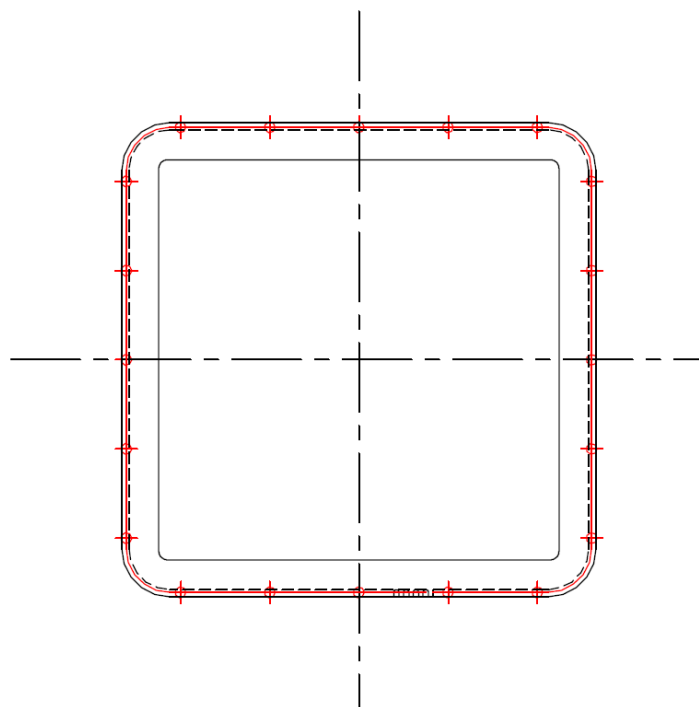


Figure 10 Cross section of mould with indicated sensor positions (red crosses) for horizontal measurement strands.

5.5 Software development and data transfer

BFI developed a software for operating the FOTS measurement system to adapt it to the application requirements at GSW. The software enables the operator to control the system, acquire and store measurement data, and visualize it online. Furthermore, the acquired data is transferred to the industrial Edge that is developed at present.

Figure 11 shows the main views of the HMI. This allows the fibres to be selected, parameterized, and calibrated for operation. Further online views visualize the line spectra, and the temperature profile of the mould in a quasi-3D representation.

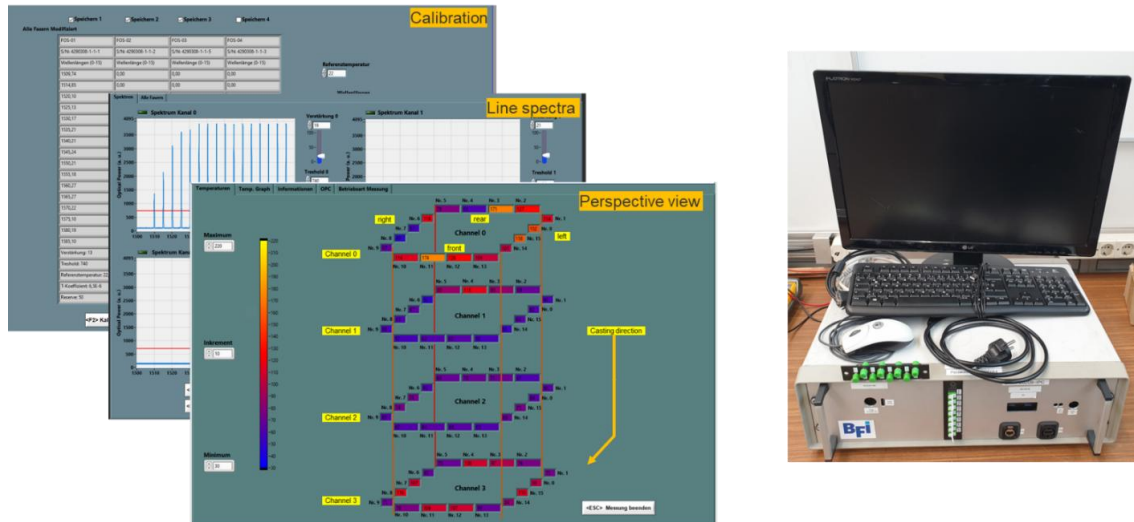


Figure 11 Left: HMI of FOTS software. Right: Detector and computing unit.

5.6 Conclusions

To improve product quality in continuous casting, a fibre-optic temperature measurement system using Fibre Bragg Gratings will be implemented on three moulds at GSW. The system enables distributed temperature sensing with 80 measurement points per mould, offering high spatial resolution.

The design includes:

- Sensor fibres embedded in copper capillaries, installed in mould grooves.
- Industrial-grade connectors and waterproof feed throughs for harsh environments.
- 4-channel layout for comprehensive coverage of mould faces and critical zones (meniscus, corners).

Data flow:

- Optical signals → Detector → Computing unit → Level2 system.
- Software provides real-time visualization, calibration, and data synchronization with casting parameters.

The next steps will be to machine the mould for the FOTS instrumentation (GSW), make software and interface adjustments and construct the mechanical and optical components for the sensor implementation at the BFI laboratory (BFI). At the same time, the necessary cable routes are being prepared for on-site commissioning (BFI+GSW).

6. Camera System for Surface Quality Inspection

6.1 Introduction

The surface condition of continuously cast billets is a crucial quality parameter, influencing both the internal structure and the downstream rolling performance. Even minor surface imperfections can propagate into defects in finished products, increasing waste and reprocessing costs.

To address this, a **high-resolution camera system operating in the visible spectrum** has been designed for **real-time inspection of the billet surface** immediately after solidification.



Figure 12 : Preliminary Concept Layout (AI generated image)

The figure presented in this section illustrates a **preliminary conceptual layout** for the positioning of the camera system along the casting strand. This initial proposal is aligned with the objectives defined in the ProcTwin project, where the development of advanced monitoring solutions for hot-surface inspection is foreseen as part of the project's technological framework.

The conceptual layout shows **two feasible sensor locations** that provide full optical access to the billet surface immediately after secondary cooling. It supports the integration principles described in later sections by indicating potential mounting positions, expected viewing angles, and the required distance from the hot strand. These elements allow an early assessment of optical coverage, mechanical feasibility, and environmental exposure under real industrial conditions.

It should be emphasized that this representation **does not constitute a final mechanical design**, but rather a **first preliminary hypothesis** intended to explore constraints and define boundary conditions for the detailed engineering phase. The final positioning will be refined jointly with **GSW**, taking into account the available structural supports, cabling routes and cooling requirements.

Unlike standard imaging systems, this camera must operate in a **harsh thermal environment**, where the billet emits significant radiation in the **red-to-near-infrared range** due to its temperature (typically between 800 and 1000 °C). This inherent emission can potentially provide **enough illumination** for imaging; however, the balance between billet self-emission and external lighting will be carefully studied.

The goal of this system is not only to detect visible defects but also to **quantify their extent**, classify their **type**, and deliver structured data to the **plant control system** to support **automatic decision-making** after each billet is cast.

6.2 Analysis performed to define the final solution

The work presented in this section focuses on the **three-dimensional evaluation of surface defects** found in steel bars supplied by **Global Steel Wire (GSW)**, with the objective of quantitatively and systematically characterizing the most recurrent defect types observed after casting and rolling operations. This activity has a predominantly experimental nature and serves as the validation basis for subsequent stages of development related to the **automatic detection and digitalization of defects** within GSW's production environment.

Unlike other studies oriented towards process modelling or simulation, the present analysis concentrates on the **acquisition, reconstruction, and processing of real geometric data** obtained through advanced optical 3D scanning technologies. This approach enables the **high-precision quantification of surface irregularities**, both in morphology and spatial distribution, creating a digital repository that combines visual, geometric, and contextual information for each sample.

The adopted methodology integrates two complementary digitization systems — a structured-light 3D scanner and a portable LiDAR sensor — which together enable **multi-scale surface capture** of the material. This combined approach aims not only to document the existing defectology but also to **compare the metrological capabilities of both systems** in terms of resolution, acquisition time, portability, and suitability for future in-line industrial applications.

Two three-dimensional scanning systems with complementary characteristics were used for surface capture and geometric analysis in order to obtain accurate images of the material.

- **Shining EinScan Pro HD 3D scanner:** This is a portable system based on structured light projection, capable of capturing high-density point clouds with a spatial resolution of up to 0.2 mm and a volumetric accuracy of ± 0.04 mm. The equipment can be operated in both manual and fixed modes, facilitating its application on objects with complex geometries or variable dimensions.

The acquisition process is managed through ExScan Pro software, which controls all stages of the workflow: optical calibration, capture, alignment, point cloud fusion, and three-dimensional mesh reconstruction.

The final models were exported in STL and OBJ formats, compatible with CAD platforms, dimensional metrology, and defect analysis using reverse engineering software.

- **iPad Pro device with LiDAR sensor:** An iPad Pro equipped with a high-resolution LiDAR sensor was used as a complementary scanning device, enabling rapid and flexible surface digitisation at a significantly lower operational cost. Although its spatial resolution (≈ 1 mm) and accuracy are lower than those of the structured-light system, its portability and ease of deployment make it particularly suitable for preliminary inspections and macroscopic defect assessment. The three-dimensional reconstructions were generated using the *3D Scanner App* and subsequently converted to OBJ format for model alignment and comparative analysis within a CAD environment against the reference scanner.

In order to establish a quantitative basis for defining strategies for correcting and improving steel bar casting processes, a three-dimensional measurement and analysis of surface defects was carried out. The main objective of this activity was to identify, classify and quantify the most recurrent defects present in steel bars supplied by the company CELSA, which were specifically selected because they presented the most common types of defects during their rolling and forming processes.

This study constitutes a preliminary phase within the framework of the project, aimed at validating three-dimensional inspection methodologies using advanced optical technologies and developing an online defect detection system for steel bars. This procedure made it possible to **establish an initial taxonomy of surface defectology**, which will serve as the foundation for correlating defect occurrence with process parameters and metallurgical conditions in later project stages. Furthermore, the results derived from this characterization will play a key role in **training and validating automatic detection algorithms**, contributing directly to the development of the future **in-line inspection system** to be implemented at GSW's facility.

The samples used consist of solid steel bars of different metallurgical compositions, in a completely cold state (without subsequent heat treatment), with lengths of 6000 mm and sides of 200 mm. These samples were chosen by CELSA's quality department according to criteria of defect representativeness.

6.2.1 Results and classification of defectology

Based on point cloud processing and surface reconstruction, different types of recurring defects were identified in the samples. Each type of defect was analysed in terms of geometry, distribution, depth and possible metallurgical or mechanical cause.

AI-generated images are shown to preserve the confidentiality and protect the industrial information of GSW. These images are used for illustrative purposes only.

- **Seams:** Longitudinal defects characterized by the presence of grooves or indentations parallel to the bar axis, with variable depth. They may appear continuously or discontinuously and affect the entire or partial length of the product. These defects usually originate from misalignments of the rolling mill rolls or material buildup in the guiding system.

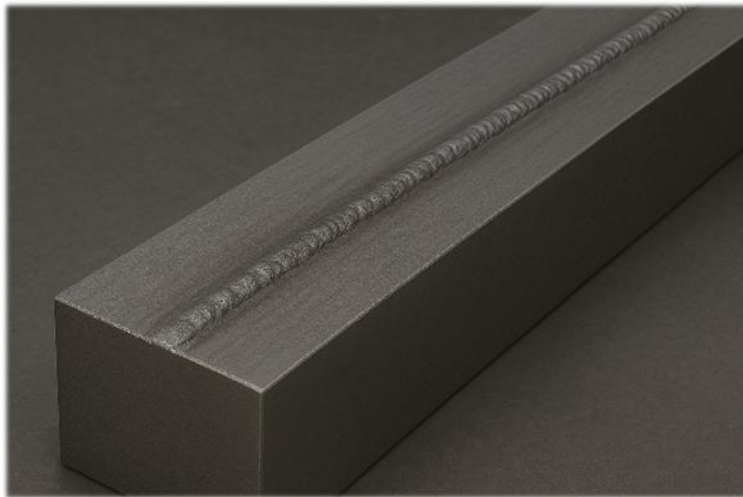


Figure 13: Seams (AI generated image)

- **Oscillation Marks:** Transverse surface defects caused by the oscillation of the mould during solidification, resulting in periodic undulations or shallow impressions on the surface. They can vary in depth and spacing, sometimes leading to localized oxidation or surface irregularities. Improper mould oscillation parameters or lubrication issues are the most common causes.

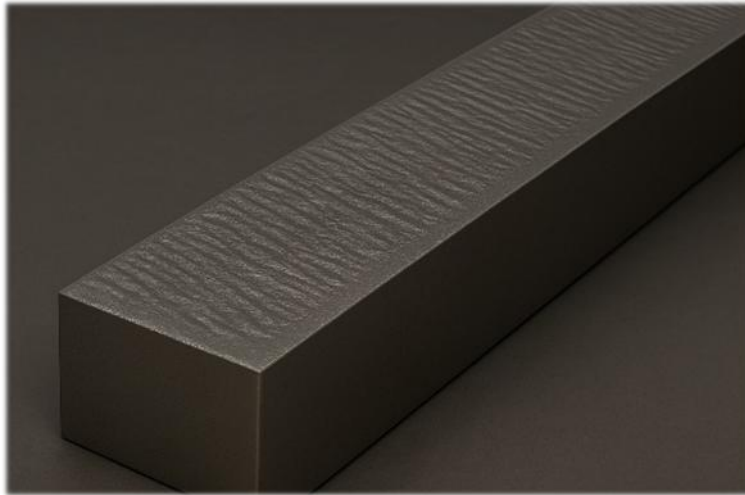


Figure 14: Oscillation Marks (AI generated image)

- **Slag Inclusions:** Irregular surface protrusions or embedded particles formed by trapped slag during the casting process. These defects are usually rough and brittle, often found sporadically along the surface. They are commonly associated with inadequate slag removal, turbulence in the mould, or contamination during pouring.



Figure 15: Slag inclusions (AI generated image)

- **Edge Defects:** Localized imperfections that appear along the edges of the bar, often in the form of cracks, folds, or excessive wear. These defects typically arise from uneven metal flow, misalignment during rolling, or mechanical stress concentration at the corners. They may compromise dimensional accuracy and surface quality.



Figure 16: Edge defects (AI generated image)

- **Mechanical Marks:** Superficial linear or irregular marks produced by contact with handling or guiding equipment. They are typically shallow but can extend over large areas of the bar. These marks are often caused by excessive friction or worn guides.

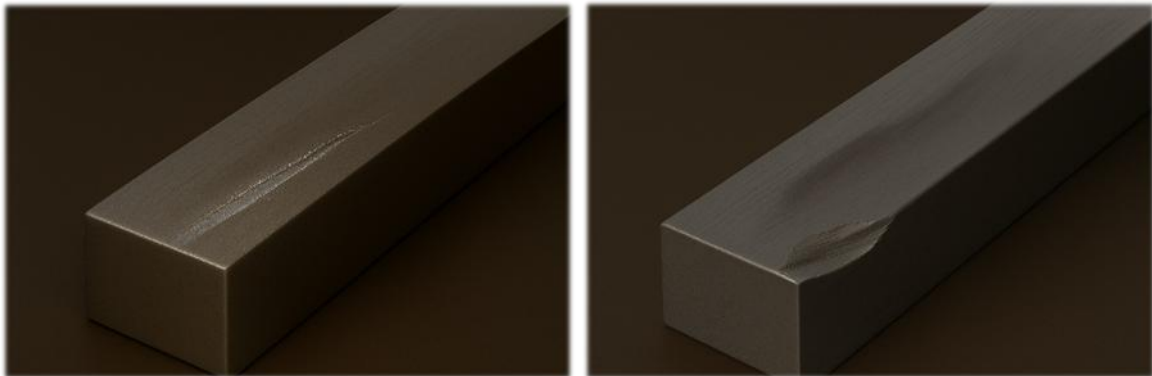


Figure 17: Mechanical marks 1 (AI generated image) Figure 18: Mechanical marks 2 (AI generated image)

- **Depressions:** Localized surface indentations or cavities of variable size and depth that disrupt the bar's geometry. They may appear isolated or in clusters and are generally produced by uneven cooling, trapped gas, or mechanical impact during handling. Their presence affects the final surface finish and mechanical integrity.



Figure 19: Depressions (AI generated image)

- **Gross Defects:** Severe surface or internal discontinuities such as deep cracks, heavy laps, or tearing. These defects can significantly weaken the material and usually result from thermal stress, poor metallurgical quality, or mechanical overstrain during deformation. Immediate inspection and removal are required to prevent failure in subsequent processing.



Figure 20: Gross defects (AI generated image) Figure 21: Gross defects (AI generated image)

- **Surface Slag:** A superficial layer of solidified slag that may appear on the bar surface during cooling. It is **not considered a defect**, as it forms naturally when residual slag solidifies on the hot surface upon exposure to air. This layer is brittle and loosely adhered, typically detaching and falling off during subsequent handling, cooling, or descaling operations. **It does not affect the internal quality** or final surface condition of the product.

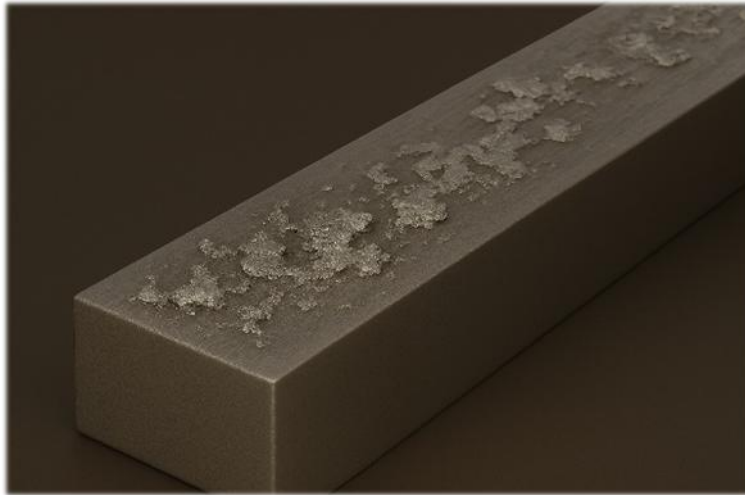


Figure 22: Surface slag (AI generated image)

Classification and Quantification of Surface Defects in Steel Bars					
Defect Type	Main Description	Characteristic Morphology	Average Dimension	Observed Frequency	Main Probable Cause
Seams	Longitudinal grooves parallel to the bar axis.	Linear, continuous or discontinuous	0.6-1 mm	High	Misalignment of rolling mill rolls or material buildup in guides
Oscillation Marks	Periodic undulations generated by mould oscillation.	Transverse, regular, shallow.	0.1-0.3 mm	Medium	Improper mould oscillation parameters or lubrication issues.
Edge Defects	Localized damage along the bar edges or corners.	Irregular, concentrated at edges.	1-1.5 mm	Medium	Uneven metal flow or localized mechanical stress.
Slag Inclusions	Surface inclusions or embedded slag particles.	Irregular, protruding.	0.8-1.2 mm	Medium	Entrapped slag during casting.
Depressions	Local surface cavities or indentations.	Elongated or oval.	1-2 mm	Medium	Uneven cooling or mechanical impact.
Mechanical Marks	Marks produced by contact with handling or guiding equipment.	Linear or irregular, superficial.	0.5-0.8 mm	High	Excessive friction or worn guiding elements.
Gross Defects	Open fissures extending along the bar axis.	Linear, with deformed edges.	0.5-2 mm	Low	Thermal stress or internal metallurgical defects.

Table 2: Surface Defects

6.2.2 Image Processing

Once the three-dimensional scans were obtained and aligned, the datasets underwent a **basic image treatment and cleaning process** aimed at improving geometric quality and facilitating subsequent analysis. During this stage, artefacts and noise generated during scanning were removed, and continuous surface meshes were created to accurately represent the morphology of the detected defects. This initial processing provided a solid basis for comparing the performance of the different acquisition systems used and for the subsequent quantitative characterization of the bar surfaces.

In a second phase, a **digital post-processing stage focused on the segmentation and automatic quantification of defects** was carried out, employing morphological analysis and threshold-based contour detection on the reconstructed meshes. From these datasets, depth profiles were extracted, cross-sectional parameters were calculated, and spatial density maps were generated to evaluate the distribution of defects along the bar length. The processed data were exported in standardized formats (CSV, OBJ, STL) for further integration into CAD and machine learning environments. This approach not only enabled a **quantitative comparison of the different defect types and their geometric characteristics** but also established a direct workflow connecting visual inspection data with predictive models and digital twin simulations to be developed in later stages of the ProcTwin project.

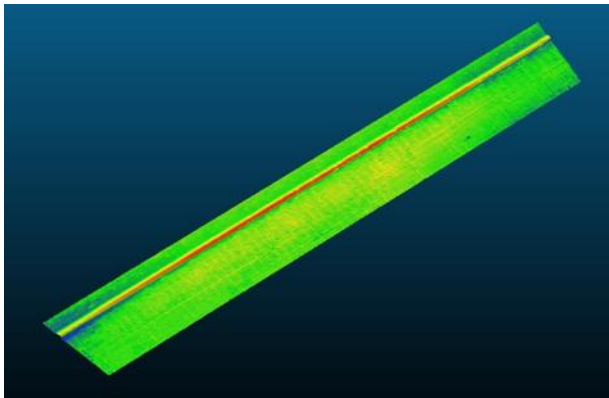


Figure 23: Seams surface inspection

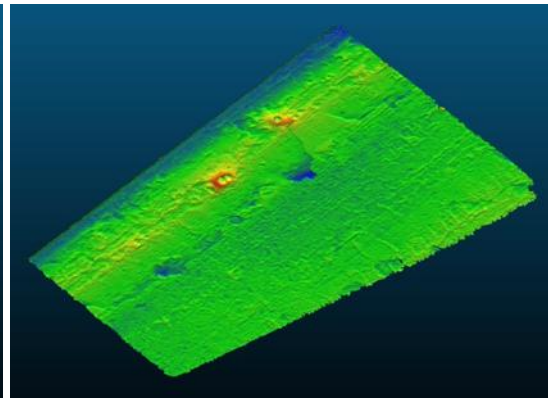


Figure 24: Slag inclusion surface inspection

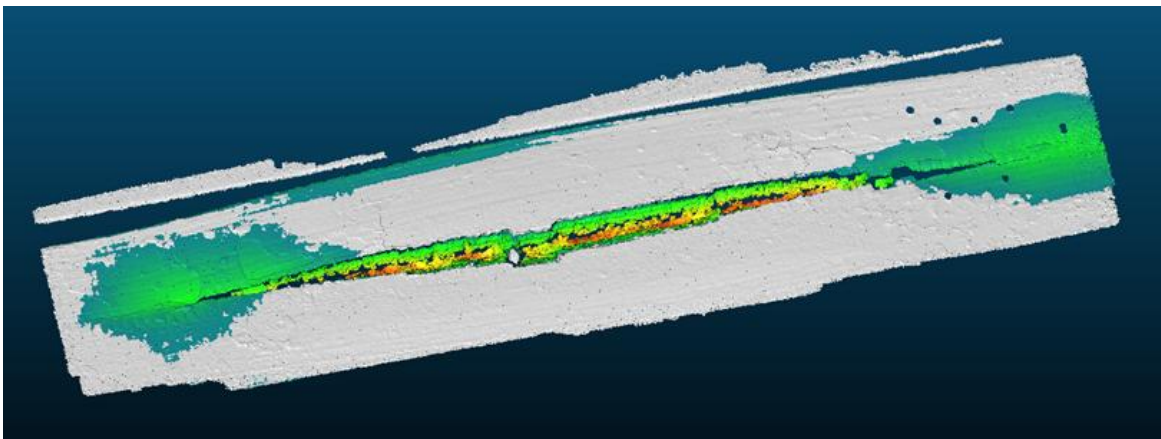


Figure 25: Gross defect surface inspection

The current dimensions of the parts have been hidden to preserve confidentiality and protect GSW's industrial information. The values shown are for illustrative purposes only.

6.2.3 Conclusions

The work carried out in this section demonstrates the feasibility of applying **three-dimensional optical scanning and digital image processing** for the detailed characterization of surface defects in steel bars. The combination of high-resolution geometric data and quantitative analysis techniques has enabled the establishment of a preliminary defect classification framework, which will serve as the foundation for future developments in automated inspection and digital twin integration. These results represent a significant step toward achieving **real-time quality control and predictive maintenance** capabilities within the ProcTwin demonstrator environment.

6.3 System Overview

The inspection unit is based on the **PN16KXGV-75KM line-scan camera** from *Hefei I-TEK OptoElectronics Co., Ltd.* This device is specifically designed for high-speed industrial imaging and is well suited to the continuous casting environment at GSW.

This is a **global-shutter CMOS camera** with a **16,384-pixel sensor** ($3.5\ \mu\text{m} \times 3.5\ \mu\text{m}$) and a **maximum acquisition speed of 75 kHz**, capable of capturing continuous imagery of fast-moving billets without distortion. The line-scan principle allows the system to acquire one line at a time and reconstruct a complete surface image as the billet moves, which is particularly advantageous for long products with uniform motion along the casting line.

Key features of this camera are outlined below:

- **High dynamic range ($\geq 53.7\ \text{dB}$) and low noise**, enabling contrast detection even under fluctuating illumination and variable billet temperature.
- **10 GigE Vision interface** with SFP+ optical connection, allowing up to **1.2 GB/s** throughput and reliable data transmission over long distances in harsh industrial environments.
- **External trigger or PWM exposure control**, synchronized with the billet movement, ensuring a consistent spatial relationship between the captured lines and the physical position on the billet.
- Built-in temperature monitoring and support for industrial environments ($0 - 55\ ^\circ\text{C}$), which facilitates safe operation inside a cooled housing close to the hot strand.

This high-speed configuration enables complete visual coverage of the billet surface, line by line, even at industrial casting speeds. In combination with the optical configuration described in the following subsection, the camera provides the resolution and acquisition rate required to detect and characterize surface defects while maintaining continuous, real-time inspection during normal plant operation.

6.4 Optical Configuration

6.4.1 Lens Specification

The camera is equipped with the **ELS-96/4.5V16K-0.07X** telecentric lens, a high-precision optical component designed for demanding industrial inspection tasks.

With a fix **0.07× magnification**, the lens provides a **wide field of view** of approximately 820 mm that matches the billet's typical cross-section of continuously cast billets. This configuration allows the system to capture the full billet width in a single line without compromising spatial uniformity.

The telecentric design plays a critical role in ensuring measurement accuracy. By maintaining constant magnification across the entire field of view, it minimizes geometric distortion and keeps constant magnification across the width, ensuring accurate measurement of defect dimensions.

When combined with the camera's 3.5 μm pixel size, the 0.07× magnification yields an effective spatial resolution of approximately **0.25 mm/pixel**. This resolution is enough for the reliable detection of a wide range of defect types commonly found in billets, including surface cracks, slag patches, oscillation marks, and edge or corner defects. It therefore ensures that the optical system provides the level of detail necessary to support robust defect identification and quantitative assessment.

6.4.2 Illumination and Thermal Emission Study

Given the high surface temperature of the billet, the **primary light source will be its own thermal emission** in the visible red and near-infrared bands. This self-emission, when appropriately filtered, can provide stable illumination for imaging without additional lighting.

However, **external LED line lighting** (with narrow-band spectral filtering) will also be evaluated if the thermal emission is not suitable for the project's objective to ensure contrast stability under variable casting conditions or during cooling transients.

A combination of **optical filters** and **exposure adjustments** will be used to maximize image quality and suppress overexposed zones caused by the glowing billet.

6.5 Installation Layout

6.5.1 Mechanical Integration

The camera module will be installed **along the strand after secondary cooling**, at a position where the billet surface is exposed and accessible. The mounting structure will include:

- **Water-cooled protective housing** with an optical window made of **quartz or sapphire** resistant to thermal radiation and slag particles.
- **Vibration isolation supports**, ensuring mechanical stability despite nearby equipment operation.
- **Motorized focus and tilt adjustment** for precise alignment during calibration.

The housing will also include a **compressed-air purge** system to prevent dust or vapour accumulation on the optical window.

6.5.2 Field of View and Alignment

The optical axis will be positioned perpendicular to the billet surface, scanning across the entire width. A **calibration target** will be used periodically to verify geometric accuracy and pixel-to-millimeter scaling.

Alignment procedures will ensure the correct overlap of successive line frames, guaranteeing image reconstruction fidelity along the billet length.

6.6 Connectivity and Operation

6.6.1 Data Communication

Image data will be transmitted via **10GigE Vision protocol** over optical fibre to a **dedicated acquisition server** located in a temperature-controlled room.

The server will perform **real-time image stitching, defect detection, and classification algorithms**.

The processing software will follow **GenICam** standards and integrate with existing SCADA or MES systems through an HTTP-based REST API using **JSON** as the data serialization format.

6.6.2 Power and Control Interface

The camera requires a DC power supply in the **12–24 V** range and is rated for a maximum input current of **2 A**. According to the manufacturer's specifications, the typical power dissipation of the device is approximately **12 W**, which reflects its current operating consumption under standard conditions.

All trigger and synchronization signals are provided by the **machine encoder** or **casting speed sensor**, ensuring accurate spatial scaling during line-scan acquisition. **Exposure** and **gain** parameters are controlled through the camera's internal automatic adjustment mechanisms, allowing the system to maintain stable image quality under varying illumination and operating conditions.

6.7 Operation Principle

The billet moves continuously along the casting line. The camera captures one line at a time; each line corresponds to a cross-section of the billet surface.

As the billet advances, these lines are concatenated into a full 2D image, forming a **continuous surface map** of the entire billet.

The acquisition and processing pipeline includes:

1. **Image acquisition** synchronized with casting speed.
2. **Flat-field correction** and **contrast normalization** to compensate for thermal intensity gradients.
3. **Defect segmentation** using texture and brightness anomalies.
4. **Defect classification** into categories defined by metallurgical relevance.

5. Computation of defect coverage ratios and severity indices.

This data is used both for visualization and for automated decision-making within the plant control system.

6.8 Environmental and Safety Considerations

The billet's environment is characterized by high temperature, dust, and electromagnetic interference. The camera system will include:

- **Thermal insulation and water cooling** for both camera and illumination if billet's self-emission is insufficient.
- **Air curtain protection** for optical surfaces.
- **Industrial-grade connectors and shielded cables** for high-EMC compatibility.
- **Safety interlocks** to disable the camera enclosure during maintenance or if cooling fails.

All components comply with **industrial EMC and CE regulations** and are designed for continuous operation in harsh foundry conditions.

6.9 Expected Performance

- **Spatial resolution:** ~0.25 mm/pixel (depending on billet size and setup).
- **Maximum inspection speed:** equivalent to billet speeds up to 3 m/s (75 k lines/s).
- **Detection accuracy:** defects $\geq 1 \text{ mm}^2$ identifiable.
- **System reliability:** designed for > 95 % uptime under industrial conditions.

The system will provide quantitative surface information at the end of each billet, supporting both **online visualization** and **offline statistical analysis**.

6.10 Data Structure and Integration with Control System

6.10.1 Data Structure Proposal

At the end of each billet, the camera system will generate a **structured data file** summarizing the inspection results. The proposed data schema (in JSON or database table form) is as follows:

```
{
  "billet_id": "C1234-2025-10-23-ShiftB",
  "timestamp_start": "2025-10-23T14:35:22Z",
  "timestamp_end": "2025-10-23T14:48:09Z",
  "length_mm": 12000,
  "width_mm": 150,
  "height_mm": 150,
```

```

"surface_temperature_C": 920,

"inspection_status": "completed",

"illumination_mode": "self-emission",

"defects_summary": {
  "total_defect_area_mm2": 5820,
  "defect_coverage_percent": 2.5,
  "number_of_defects": 27
},

"defects_by_type": [
  { "type": "seam", "count": 5, "area_mm2": 1200 },
  { "type": "oscillation marks", "count": 4, "area_mm2": 900 },
  { "type": "edge defect", "count": 2, "area_mm2": 700 },
  { "type": "slag lump", "count": 3, "area_mm2": 800 },
  { "type": "depression", "count": 7, "area_mm2": 1400 },
  { "type": "mechanical marks", "count": 4, "area_mm2": 820 },
  { "type": "gross defects", "count": 2, "area_mm2": 300 }
],

"defects_detailed": [
  {
    "defect_id": 1,
    "type": "seam",
    "position_start_mm": 3500,
    "position_end_mm": 3560,
    "face": "long_side_1",
    "area_mm2": 240
  },
  {
    "defect_id": 2,
    "type": "oscillation marks",
    "position_start_mm": 7800,
    "position_end_mm": 7820,
    "face": "top",
    "area_mm2": 120
  }
  // ...
],

"decision": {
  "classification": "rework",
  "criteria": "total defect area > 2%",
  "operator_validation": false
}

```

```

    },
    "image_storage_path": "/data/inspection/C1234-2025-10-23/",
    "processing_log": "OK"
}

```

This structure allows the control system to easily interpret quantitative defect information, correlate it with process data (e.g., mould oscillation, cooling parameters), and decide whether the billet should be accepted, reprocessed, or rejected.

6.10.2 Communication with the Control System

The inspection server will send summarized data to the plant's **SCADA/PLC system** through an **HTTP**-based interface over **TCP/IP**, using **JSON** as the data serialization format.

The control system will then:

- Display inspection status in the operator HMI.
- Trigger alarms if defect thresholds are exceeded.
- Store inspection data in the **plant quality database**.
- Optionally link results to the **casting lot ID** for full traceability.

The communication protocol will ensure synchronization between billet tracking and inspection results, guaranteeing each billet's unique data record.

6.11 Conclusions

The **surface quality camera system** represents a key technological component for the digitalization of the continuous casting process. Its combination of high-resolution optical sensing, robust mechanical integration, and advanced data handling capabilities provides a solid foundation for reliable, real-time monitoring of billet surface conditions. By leveraging the billet's natural thermal emission as the primary illumination source, the system reduces the need for dedicated external lighting, simplifies installation, and increases operational robustness in the harsh casting environment.

The proposed data structure enables a clear and process-oriented representation of inspection results, facilitating rapid interpretation and decision-making within the plant control system. This structured and machine-readable output supports automated quality assessment, reduces the risk of operator-dependent variability, and contributes to improved yield, enhanced process traceability, and strengthened quality assurance practices across the production line.

The next phase of the project will focus on on-site validation of illumination conditions, calibration of defect detection thresholds, and fine-tuning of processing parameters under real operational scenarios. Additionally, integration of the inspection results into the plant's supervisory control layer will be carried out to ensure seamless interoperability with existing systems and to enable full end-to-end digital connectivity within the ProcTwin framework.

7. Summary and Conclusions

Task 8.3 has successfully completed the design and preparation phase for the three monitoring systems foreseen in ProcTwin: the camera system for mould powder inspection, the fibre-optic temperature measurement system, and the surface-quality inspection camera. For each sensor, requirements were jointly analysed with GSW, suitable technologies were identified, and the corresponding installation concepts, protection measures, data-transfer principles and software functionalities were defined. The resulting designs demonstrate a high level of maturity: optical configurations have been selected, mechanical integration concepts have been proposed for the harsh casting environment, and data-communication schemes have been aligned with plant interfaces. All three sensors are therefore ready to proceed to assembly and laboratory testing.

After the fundamental concepts have been finalised with this deliverable, several elements will be further refined inside WP9 before validation at GSW. For the mould powder monitoring system, the first on-site trial will be used to confirm thermal protection needs, dust mitigation and the final camera positioning. For the fibre-optic temperature system, machining of the mould and preparation of the connector boxes and cabling routes must be completed, together with calibration adjustments in the software. For the surface-quality camera, further optimisation of image capture under real casting conditions and confirmation of optical access along the strand remain open points. These activities will ensure that the sensors operate reliably and deliver the expected data quality once installed.

The outputs of Task 8.3 provide the technical foundation for the integration activities planned in WP9. The data structures, communication principles and sensor-interface concepts defined in this deliverable will guide the connection of the three monitoring systems to the project's data-management infrastructure. As the sensors progress toward installation and commissioning, WP9 will ensure that mould powder coverage indicators, distributed temperature measurements and surface-quality data are harmonised, stored and made accessible for modelling activities and digital-twin development. This integration will enable the new sensors to contribute effectively to ProcTwin's predictive and optimisation capabilities across the continuous casting process.