WHITE PAPER

XR on the line: visualizing on-coil quality with augmented reality

SurfConInspect White Paper
Series 3/10

About Us

WHO WE ARE

SurfConInspect (SCI) is a European project funded by the Research Fund for Coal and Steel (RFCS). Our consortium brings together leading steel producers, research institutes, technology developers and innovation experts.

The partners combine industrial expertise, academic knowledge and advanced digital solutions to transform the way steel quality is controlled.

OUR MISSION

The steel industry faces increasing pressure to become more sustainable, efficient and competitive—key goals of the European Green Deal.
Our mission is to enable zero-defect manufacturing in flat steel production by:

- Detecting surface defects earlier and more accurately.
- Reducing waste and improving resource efficiency.
- Supporting operators with advanced visualization tools.
- Providing real-time control actions directly in production lines.

MAIN ACTIVITIES

- Industrial trials in tin-plate and automotive steel production.
- Development of AI-based inspection methods.
- Application of AR for real-time operator support.
- Creation of open datasets to enhance research and industrial collaboration.
- Dissemination of results to industry, research and society through events, publications and digital platforms.

EXPECTED RESULTS

- Zero-defect production through optimized inspection and control.
- Reduced waste and energy consumption, contributing to the
  European Green Deal.
- Higher competitiveness for European steel producers.
- Transferable technologies with potential applications beyond the steel sector.
- Improved working conditions, with operators supported by innovative visualization and decision-making tools.

Executive Summary

Advanced inspection systems are generating increasingly rich and heterogeneous datasets, combining geometric information from depth-aware sensors with material-sensitive signals derived from spectral analysis. Within SurfConInspect, this evolution reflects a broader shift in surface quality control: inspection is no longer limited to detecting visible anomalies but increasingly aims to reconstruct a multi-dimensional view of the strip condition in real time. Yet the industrial value of this data does not lie in its quantity alone. It depends on whether the information can be made usable, interpretable, and actionable within the operational reality of production lines.

In pickling lines and other high-speed steel processes, operators work under conditions of continuous material flow, limited reaction time, and tightly coupled process dependencies. Surface inspection events are generated at production speed and often relate to defects whose significance depends not only on classification, but also on location, severity, and downstream implications. Under these conditions, operators and process supervisors must interpret inspection outputs quickly and make decisions under time and operational pressure. The challenge is therefore not only one of sensing accuracy, but of decision support: how to translate inspection outputs into forms that fit the operator's cognitive and spatial working environment.

Traditional defect reporting methods—lists, static monitor views, alarm messages, or abstract indicators—provide information, but often detach that information from its physical context on the moving coil. This separation matters. When data is presented outside the spatial frame in which action must be taken, the operator must mentally reconstruct the relation between defect position, material movement, and intervention point. In practice, this increases cognitive load, slows response times, and can introduce inconsistency in quality decisions, especially in environments where multiple quality-relevant signals compete for attention. The limitations of this model are already implicit in the SurfConInspect rationale: as inspection systems become more precise and more complex, the human–machine interface becomes a decisive part of the quality control chain rather than a secondary display layer.

This white paper introduces the role of extended reality, and more specifically augmented reality, as a tool for real-time, on-coil quality visualization. In the SurfConInspect perspective, AR is not treated as a standalone digital novelty, but as a practical interface layer that connects advanced sensing with operator-oriented action. By embedding inspection data directly within the operator's spatial field of view, AR technologies make it possible to anchor quality information to the physical product itself, reducing abstraction and supporting more immediate interpretation. This is particularly relevant in recoiling and inspection-related operations, where the synchronization between detected defect position and visible coil position becomes essential for effective intervention.

Within SurfConInspect, AR-based visualization is explored as a demonstrator that bridges advanced sensing and human-centered quality control. The project investigates how detected defects and repair-related information can be spatially mapped onto the inspected coil through mobile and wearable devices, with attention to synchronization, usability, and robustness in industrial conditions. In this sense, AR becomes the final operational layer of the inspection ecosystem: not replacing sensing, classification, or supervisory logic, but making their outputs usable where decisions are actually made.

From detection to action: the human dimension of quality control

Inspection technologies—whether based on conventional 2D imaging, 3D depth measurement, or hyperspectral analysis—are delivering an increasingly detailed characterization of steel surface condition. Across the SurfConInspect framework, these technologies contribute complementary layers of information: visual contrast, topographic geometry, and material-sensitive spectral response. This progression marks an important step forward in inspection capability, but it does not automatically translate into better quality control. Inspection becomes operationally valuable only when its outputs can be interpreted and acted upon within the tempo and constraints of production.

In flat steel prodution, the human dimension remains central because decisions are still made by operators and process supervisors who must interpret inspection outputs in real time. This is especially true in process stages where a detected defect can trigger immediate operational consequences, such as inline cutting, speed adaptation, downstream flagging, or repair planning. The SurfConInspect requirements make this explicit: the system is expected not only to detect and classify defects, but to produce control-relevant results within operationally meaningful time windows, in some cases within 10 seconds, so that recommendations can still influence the ongoing coil process.
The working context of the operator explains why this transition from detection to action is so critical. Pickling lines run at high strip speeds and under continuous material flow, while multiple process variables and quality signals evolve simultaneously.

The operator has limited reaction time and must take decisions within a tightly interconnected production environment, where one intervention may affect quality, scrap, throughput, and downstream stability at the same time. In the RAS industrial context described in the project, for example, the operator may need to decide whether a defect should be edge-cut, cut out at the strip head or tail, or left for later treatment, depending not only on defect severity but also on position and likely downstream impact.
Under such conditions, the value of inspection depends as much on presentation as on detection accuracy. A technically correct classification is not enough if the information reaches the operator in a form that is too abstract, too delayed, or too detached from the physical situation on the line. This is where the transition from sensing to decision support becomes decisive. Inspection systems must not only detect and classify defects, but also present the resulting information in a way that supports rapid, reliable, and repeatable decision-making by human users operating under pressure.
Conventional human–machine interfaces often rely on tabulated defect lists, 2D plots, alarm messages, or monitor-based inspection views. These are informative from a technical standpoint, but they frequently separate data from its spatial and operational context. In practice, the operator is required to reconstruct mentally where the defect is located, how severe it is, whether it is isolated or part of a broader pattern, and what action is feasible at that exact moment in the process. As inspection datasets become richer and more multi-dimensional, this gap between data generation and human interpretability becomes more pronounced. That is the point where visualization ceases to be a secondary interface issue and becomes a core component of modern quality control architecture.

Real-time visualization in online inspection systems

Real-time visualization is a critical requirement in online inspection environments because the usefulness of inspection data decays rapidly if it is not presented in a form that matches the tempo of production. In high-speed lines, even short delays or unclear representations can have direct operational consequences. A defect that is detected correctly but visualized too late may no longer allow timely intervention. Conversely, when the meaning of the signal is uncertain, operators may respond with overly conservative actions—such as unnecessary slowdowns, excessive rejection, or precautionary process adjustments that protect quality at the expense of yield and throughput. In other cases, ambiguity can lead to inconsistent decisions between shifts or operators, reducing the repeatability of quality control.

This issue becomes more pronounced as inspection systems evolve. The SurfConInspect approach combines multiple data sources and processing layers, including real-time measurements, upstream production information, and improved quality data derived from advanced sensing and classification modules. The result is a much richer picture of strip condition, but also a much greater volume of information that must be made operationally intelligible. In this context, classification accuracy alone is not sufficient. The inspection chain must include visualization strategies capable of transforming complex outputs into meaningful insights that can be understood and acted upon under production pressure.

In pickling lines, visualization is particularly challenging because inspection events are not static. They are spatially distributed along the strip, related to edge or centre position, clustering, and local severity, and at the same time they are temporally distributed along the coil as the material advances continuously through the process. A meaningful visualization system must therefore preserve spatial relationships between defects and material position, so that the operator can understand not only that a defect exists, but where it is and how it relates to the moving product. It must also indicate severity and classification in a way that is immediately legible, reducing the need for secondary interpretation. This is fully consistent with the project logic, where quality processors generate quality events and supervisory components translate them into control actions that are only useful if they remain synchronized with the actual process state.

The importance of this synchronization is evident in the operational requirements defined for SurfConInspect. For use cases related to automated cutting control and process adaptation, the control result must be available within a short time window and submitted to the operator while the relevant coil section is still actionable. This means that visualization is not an afterthought layered on top of analytics, but an integral part of the response chain linking sensing, assessment, and intervention. If the representation fails to preserve the physical and temporal coherence of the data, the value of the upstream inspection effort is weakened.

For this reason, visualization in online inspection systems should not be understood as a simple display function. It is a decision-support function. Its role is to reduce the cognitive distance between measured defect data and operator action, making the inspection result usable in the moment it matters. In a modern quality control architecture, this function becomes just as important as detection and classification themselves, because it determines whether advanced sensing can actually influence the process in real time.

On-coil defect visualization concepts

A central concept in advanced inspection visualization is the mapping of defect data onto the physical representation of the coil rather than onto an abstract reporting structure. In industrial quality control, this shift is more than a graphical refinement. It changes the way inspection results are interpreted by aligning information with the geometry and movement of the actual product. Within the SurfConInspect logic, this is particularly relevant because defect events are generated from position-synchronized measurements and quality models that already relate inspection data to specific coil segments and material tracking information.

Instead of presenting detected anomalies as isolated database entries, on-coil visualization associates each defect with its physical position along the strip and, where relevant, across the strip width. This spatial correlation gives operators immediate access to patterns that are difficult to reconstruct from lists alone. It becomes possible to see whether defects are concentrated in the head or tail of the coil, near the edge, or repeatedly appearing in the same zone. This is operationally important because the project evidence shows that position is one of the decisive parameters in assessing criticality, particularly for topographic defects linked to downstream coil-break risk, where a strong concentration near strip edges has been observed.

Such a representation supports several layers of interpretation at once. Operators can identify clustering patterns, assess how defects are distributed over the coil length, and distinguish between isolated events and systemic phenomena that may point to an ongoing process issue. A single defect may require local action; a repeated sequence of defects may instead indicate that a process condition has shifted and that broader corrective action is needed. This form of contextual awareness cannot be derived with the same clarity from numerical tables or alarm sequences, because those formats tend to fragment information that is spatially and operationally connected.

Interpretability is further enhanced when spatial localization is combined with severity encoding. If the visualization model uses clear visual variables—such as color, symbol type, or intensity—to distinguish defect class and criticality, the operator can assess not only where defects are located, but also how relevant they are from a quality-control standpoint. In the SurfConInspect perspective, this is consistent with the broader architecture in which quality processors convert raw inspection data into quality indices and events, and supervisory logic translates these into actionable outputs. A coherent on-coil visualization becomes the human-readable counterpart of this logic: it exposes location, classification, and severity in a single operational view.

When these dimensions are integrated coherently, the result is not simply a better display, but a more actionable representation of product quality. The operator gains a clearer overview of coil status, can recognize meaningful patterns more quickly, and can relate inspection outputs directly to feasible intervention points on the material. That is the essential contribution of on-coil visualization: reducing the gap between data structure and physical process reality.

Augmented reality in industrial contexts

Augmented reality refers to a class of technologies that superimpose digital information onto the physical environment in real time, enabling the user to perceive both the material scene and the relevant data within a single visual frame. In industrial applications, this distinction is important because the value of AR does not lie in immersion for its own sake, but in its ability to connect operational information directly to the physical object or process to which that information refers. Within the SurfConInspect context, this means linking inspection outputs to the moving steel product in a way that preserves spatial meaning and supports immediate interpretation.

In production environments, AR differs from conventional screen-based human–machine interfaces because the information is not simply displayed nearby, but spatially anchored and context-aware. A traditional HMI requires the operator to alternate attention between the line and a remote display, mentally translating defect positions, severity indicators, or repair instructions into the physical coordinates of the material. AR changes this interaction model by placing the information within the operator's field of view and aligning it with the product itself. This reduces the abstraction involved in defect interpretation and makes the inspection result easier to relate to the actual coil section under consideration. This contextual embedding offers several operational advantages. The first is a reduction in cognitive switching. Instead of moving repeatedly between the physical line and a separate monitor, the operator can perceive relevant inspection cues within a single visual workflow.

The second is faster correlation between data and material, which is especially important when decisions depend on the precise location of a defect along the strip or coil. The third is improved situational awareness, because the operator no longer receives information as a detached signal, but as part of the live production context in which action must be taken. These benefits are particularly relevant in the kind of high-speed environments addressed by SurfConInspect, where the time available for interpretation and intervention is inherently limited.

The project documentation also frames AR within a broader industrial evolution in human–machine interaction. Recent generations of mobile and wearable XR devices, including tablets and smart glasses, have made it possible to project digital information into real operational spaces with increasing positional accuracy. This is especially significant in steel production, where one of the long-standing challenges has been the synchronized visualization of quality information on a moving product. In SurfConInspect, this challenge is addressed not as a generic visualization exercise, but as a concrete use case tied to recoiling-line process improvement and on-coil defect localization.

It is important to stress that AR is not intended to replace existing control systems or supervisory platforms. The underlying inspection, classification, and process-control logic remains essential and continues to operate through established architectures. What AR contributes is a different interface layer, one that enhances how inspection information is perceived and interpreted by the human operator. In that sense, AR acts as an enabling complement: it does not alter the control system's function, but strengthens the link between advanced sensing and effective operational decision-making.

Operator decision support through XR

Extended reality systems, including augmented reality, have the potential to transform raw inspection outputs into actionable insights by changing not the underlying data itself, but the way that data is delivered to the operator at the moment of decision. In the SurfConInspect perspective, this is a critical step in the inspection chain. Advanced sensing modules may generate increasingly precise information on defect geometry, material condition, and quality status, but this information only becomes operationally valuable when it supports timely, consistent, and well-founded human judgement.

Decision support in this context begins with the ability to highlight critical defects in a way that stands out immediately within the operator's visual and cognitive workflow. Rather than requiring the user to search through lists, cross-reference alarm messages, or interpret abstract coordinates, XR-based systems can draw attention directly to the most relevant quality events. This becomes especially useful in production environments where the operator must distinguish between defects that require immediate intervention and those that can be tolerated, monitored, or deferred to a later process step. In several SurfConInspect use cases, this distinction is central to the control logic itself, since different actions may be appropriate depending on severity, position, and expected downstream impact.

A second and equally important function is the support of borderline decision-making. Many quality decisions in steel processing are not binary in the intuitive sense. A defect may not be obviously critical, yet may still warrant caution depending on customer requirements, strip location, material characteristics, or clustering patterns. In these situations, XR can help by presenting defect attributes—such as type, severity, or recurrence—in a structured and visually coherent form. Graphical encoding through colour, symbolisation, positional overlays, or intensity allows complex inspection outputs to be interpreted more quickly and more consistently than purely textual or tabular representations.

This also has an organizational value. One of the recurring challenges in inspection-based decision-making is variability between operators. When quality information is presented in fragmented or overly abstract ways, interpretation depends more heavily on individual experience and mental reconstruction. XR-based interfaces can reduce this variability by standardizing how criticality and context are visualized, supporting a more consistent interpretation across operators, shifts, and operating conditions. The effect is not to remove human judgement, but to make that judgement more transparent and better supported by the structure of the interface.

This is particularly relevant in environments where inspection systems generate large volumes of data continuously. As sensing becomes more advanced, the risk is not only missing defects, but also overwhelming the operator with too much information presented in a form that is difficult to prioritize. XR helps address this by reducing ambiguity and preserving context. When inspection data is shown in a structured and spatially meaningful way, the operator can understand not only what was detected, but why it matters and where it matters. That is the core contribution of XR to decision support in quality control: turning inspection outputs into operational understanding without separating the information from the physical process in which action must be taken.

The SurfConInspect AR demonstrator

Within SurfConInspect, an AR demonstrator is being developed to explore the real-time visualization of on-coil quality information as part of an integrated inspection workflow. Its role is not isolated from the rest of the system, but positioned at the point where sensing results become operationally visible to the user. In the project architecture, this corresponds to the transition from measurement and quality-event generation to human interpretation and action. The demonstrator is therefore closely connected to the broader SCI framework, in which quality processors transform raw inspection data into quality indices and events, and supervisory logic supports the definition of control actions.

The demonstrator integrates outputs from advanced inspection modules, including geometric and material-sensitive systems, and presents them in a context-aware visualization environment. This reflects the wider SurfConInspect approach, where different sensing modalities contribute complementary information: 3D inspection provides depth and morphology, spectral methods contribute material-sensitive insights, and the AR layer makes these outputs accessible in a spatially meaningful way for the operator. Rather than viewing visualization as a separate subsystem, the project treats it as the interface through which the value of advanced inspection can be translated into practice.

A particularly important design aspect concerns synchronization with the physical coil. The project documentation identifies the encoder signal of the recoiling line as a key data source for aligning XR visualization with the actual coil position seen by the operator. At the same time, content from the XR system must be linked to data provided by the quality database and the material-tracking system, so that repair-related and inspection-related information can be mapped correctly to the coil section under observation. This synchronization requirement is central to the value of the demonstrator: if visualization is not precisely aligned with material position, the contextual advantage of AR is weakened.

Robustness in industrial conditions is another essential requirement. The demonstrator is conceived for use in real production environments, which means that usability cannot be separated from environmental constraints. The system must remain understandable and effective under operational pressure, while also respecting industrial conditions related to timing, continuity of operation, and integration with existing infrastructures. This is consistent with the software requirements of the project, which emphasize continuous operation, real-time behaviour, modularity, and actionable results delivered within operationally relevant time frames.

Low-latency data synchronization and clarity of visual encoding are equally important. The demonstrator is not designed to display all available information indiscriminately, but to present defect severity and classification in a way that supports immediate interpretation. This requires a careful balance between richness of data and readability of interface. If advanced sensing produces detailed outputs but the visualization remains ambiguous, the operational gain is lost. For this reason, the demonstrator focuses on making classification, severity, and location legible within a single context-aware view, aligned with the operator's task rather than with the internal structure of the data pipeline.

The objective, then, is not to introduce a standalone visualization novelty, but to validate how XR-based interfaces can improve operator interaction with advanced inspection data. By linking sensing outputs directly to operator perception, the demonstrator represents the last operational layer of the inspection chain: from acquisition, to analysis, to informed decision-making. In this sense, it embodies one of the most distinctive contributions of SurfConInspect, namely the attempt to close the gap between increasingly sophisticated inspection systems and the human decisions that still determine process response on the line.

Industrial constraints and implementation considerations

Introducing XR technologies into flat-steel production environments requires addressing a set of practical constraints that are typical of industrial steel processing and that directly affect the feasibility of real-time visualization. These are not peripheral concerns, but core design conditions. Humidity, vibration, and lighting variability are all characteristic of the production context and can influence both the stability of the visualization interface and the operator's ability to perceive information clearly. In a line environment, digital overlays must remain intelligible despite reflections, motion, and changing visual conditions, while the hardware must tolerate continuous exposure to demanding operational surroundings.

Safety and ergonomics are equally decisive. An XR interface in an industrial setting cannot compete with the operator's primary visual attention or introduce unnecessary distraction. It must support the task without obstructing the physical environment, and it must fit naturally into the operator's workflow. This is one of the reasons why SurfConInspect positions AR as a complement to existing control systems rather than as a replacement for them. The purpose is to enrich perception with contextual information, not to burden the operator with an additional layer of visual complexity. In this sense, usability is not a generic software property, but a condition for safe and effective deployment in production.

System reliability and maintainability also become critical once XR moves from concept to plant-level use. In the SurfConInspect architecture, visualization is linked to real-time inspection outputs and therefore depends on the continuity and robustness of upstream data flows. If the interface is to support operational decisions, it must behave consistently over time, remain compatible with plant IT requirements, and integrate without disturbing existing production systems. This is fully aligned with the project requirements, which emphasize continuous operation, modularity, and local integration without disrupting the production environment.

Among the implementation constraints, data latency is particularly critical. Visualization must remain synchronized with strip or coil movement in order to preserve spatial accuracy. If there is a temporal mismatch between detected defect position and displayed overlay, the operator may act on the wrong physical location, undermining the main benefit of contextual visualization. The project documentation makes clear that, for the XR-related use case, synchronization depends on combining recoiling-line encoder signals with repair and inspection data from the quality database and material-tracking system. This requirement is not merely technical; it is fundamental to preserving trust in the interface and to ensuring that AR remains operationally credible.

Scalability and adaptability are another important consideration. XR systems in this context should not be designed around a fixed set of inspection outputs only. As the broader inspection ecosystem evolves—through improved classifiers, additional sensing modules, or new quality models—the visualization layer must be able to incorporate new information without requiring a complete redesign. For this reason, interoperability and modular integration are key design principles. The XR interface must remain connected to the wider SurfConInspect logic, capable of receiving structured outputs from different modules while maintaining a coherent and readable operator experience. That is what makes implementation sustainable over time: not only technical feasibility in a single demonstrator, but the ability to remain aligned with a growing and evolving inspection architecture.

Conclusions

Inspection technologies continue to evolve in sensing capability, generating increasingly detailed information on surface geometry, material condition, and defect behavior. Yet the industrial value of inspection does not depend on sensing performance alone. It depends on whether that information reaches the operator in a form that supports timely, reliable, and context-aware decisions. In production environments such as pickling and recoiling lines, the difference between detection and action is often determined not by the quality of the sensor, but by the quality of the interface between data and human judgement.

XR-based visualization, and in particular augmented reality, offers a structured way to embed inspection data within the operator's working context. By enabling real-time, spatially anchored visualization of defects on or in relation to the physical coil, AR strengthens the connection between sensing and decision-making. It reduces the abstraction that characterizes conventional screen-based reporting and makes inspection outputs easier to interpret under operational pressure. In this sense, AR does not simply improve how information is displayed; it changes how quality information becomes actionable.

Within this framework, SurfConInspect contributes by systematically integrating advanced inspection outputs into operator-oriented visualization environments and by addressing a transition that is often overlooked in inspection system design: the passage from data generation to operational decision-making. While the previous white papers focused on geometric sensing through 3D inspection and material-sensitive sensing through hyperspectral analysis, this work extends the inspection paradigm to the human–machine interaction layer. That extension is essential, because complex inspection results only create operational value when they remain understandable and usable under real production constraints.
The project investigates how on-coil defect data, derived from depth-aware and spectral inspection modules, can be spatially contextualized and visualized through augmented reality in high-speed industrial environments. This includes the synchronization of visualization with coil movement through encoder-based position tracking, the integration of inspection and repair-related data through the quality database and material-tracking systems, and the design of interfaces that remain robust, legible, and operationally relevant. These are not accessory features, but enabling conditions for making AR credible as part of an industrial inspection workflow.
By validating an AR demonstrator under industrially relevant conditions, SurfConInspect advances the state of practice toward a more cohesive inspection ecosystem in which sensing, analysis, and operator interaction are closely connected. The project shows that the future of surface quality control is not defined only by better sensors, but by better integration across the full chain of inspection. In that perspective, AR becomes the interface that makes advanced inspection operationally visible, supporting more consistent, transparent, and data-driven quality decisions in flat steel production.

The Consortium

SurfConInspect unites a diverse group of partners:

- **Steel producers:** thyssenkrupp Rasselstein (RAS), Salzgitter Flachstahl (SZFG)
- **Research & Academia:** VDEh-Betriebsforschungsinstitut (BFI), Scuola Superiore Sant'Anna (SSSA), CETIC
- **Technology developers:** Clecim France (CLECIM)
- **Communication & dissemination experts:** yourscienceEDU (YSE)

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Together, we are shaping the future of **sustainable steel production**.