SURF CON INSPECT

WHITE PAPER



Speed vs scale: controlling pickling-line speed with aggregated indices

SurfConInspect White Paper
Series 8/10

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

Pickling-line speed is one of the primary determinants of productivity in flat steel production. A line that runs faster processes more material per unit time, reduces the cost per tonne of the pickling operation, and improves the utilisation of upstream hot rolling capacity. Speed is bounded, however, by the chemical kinetics of the pickling reaction: at any given combination of acid concentration, temperature, and strip surface condition, there is a maximum throughput rate above which the acid does not have sufficient residence time to dissolve the scale layer completely, leaving residual oxide on the strip surface that compromises the adhesion of downstream coatings and the surface quality of the finished product.

The practical consequence of this constraint has historically been conservative speed settings calibrated to the worst-case surface condition expected within each material grade. Coils whose actual scale affection is lower than the worst-case assumption, which represents the majority of production in a well-controlled rolling campaign, are processed at a speed that is lower than their actual surface condition would permit. The productivity loss is systematic and cumulative, but it has been accepted as the price of the information deficit that characterises conventional pickling-line operation: without a direct, coil-specific measurement of scale coverage in real time, line speed cannot be adapted to the material being processed. It can only be set to a level that is safe for the most demanding case anticipated.

This white paper addresses the nature of scale as a surface phenomenon, the physical relationship between scale affection and pickling residence time, and the approach developed within the SurfConInspect project to quantify scale coverage in real time and use this measurement as the basis for continuous speed adaptation. The central concept is the aggregated quality index, a scalar quantity computed from inspection data that represents the fractional coverage of residual oxide on the strip surface over a defined inspection window, and that provides the input to a speed control logic capable of responding to the actual scale condition of each coil section rather than to a static grade-based assumption.

This use case is one of the four industrial use cases implemented within SurfConInspect, specifically at the thyssenkrupp Rasselstein (RAS) pickling line in Andernach. Its integration within the quality processor and online quality supervisor architecture - described in WP6 of this series - and its dependence on the two-dimensional inspection channel of the combined 2D/3D system described in WP5 place it within a broader quality control infrastructure that simultaneously monitors topographic defect severity, scale affection, and, at finishing lines, online grading criteria. The quantitative target associated with this use case is a one percent increase in pickling-line yield through optimised speed management, a figure whose operational significance at the throughput levels of the RAS facility is substantial.

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Scale formation and its significance in pickling-line processing

Scale is the iron oxide layer that forms on the surface of hot-rolled steel strip through oxidation of the steel surface at the elevated temperatures of the hot rolling process. The resulting oxide is not a chemically uniform layer: it is a composite of three distinct phases, wüstite (FeO), magnetite (Fe_3O_4), and haematite (Fe_2O_3), whose relative proportions depend on the temperature profile of the rolling pass and the cooling conditions applied after rolling. In hot-rolled strip destined for tin-plate and automotive applications, this layer is typically between 5 and 20 micrometres thick. It must be removed before cold rolling, coating, or any further surface treatment, because iron oxide is chemically incompatible with the adhesion requirements of both metallic and organic coatings.

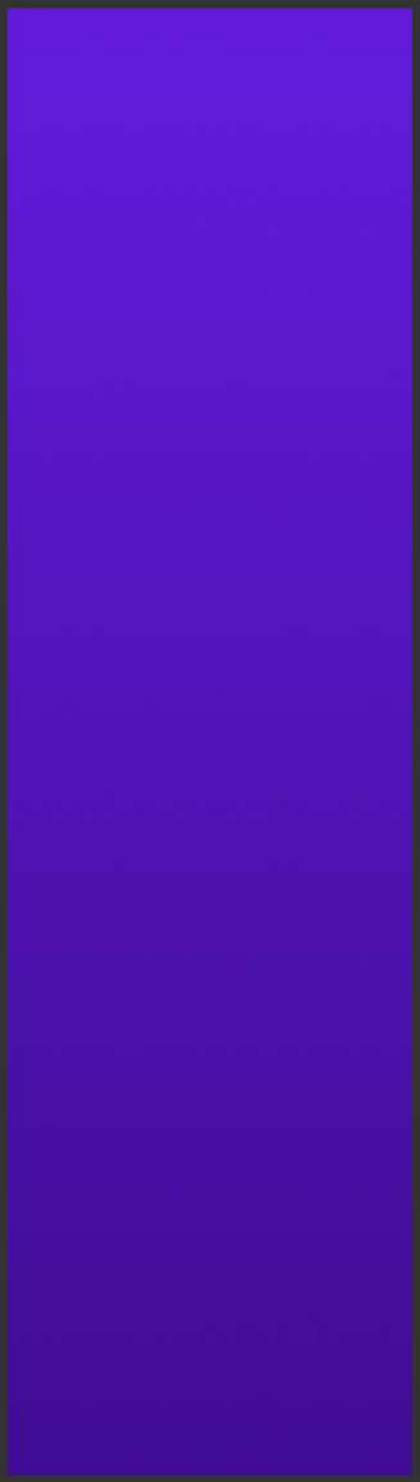


The three oxide phases dissolve at substantially different rates in sulfuric acid under typical pickling conditions. Wüstite dissolves significantly faster than magnetite, which in turn dissolves faster than haematite. The resistance of the scale layer to chemical removal therefore depends not on its total thickness alone but on its phase composition, a quantity that reflects the thermal history of the hot rolling process and varies from coil to coil and, within a single coil, along its length as the strip temperature falls during rolling. A coil head that has cooled more slowly and accumulated a higher wüstite fraction will pickle faster than a coil tail whose oxide layer is proportionally richer in magnetite. This compositional variability is one of the reasons why a single fixed speed setting cannot be simultaneously optimal for all coils processed on the same line, even within a nominally homogeneous material grade.

At the RAS pickling line in Andernach, the material range encompasses hot-rolled coils for tin-plate production, one of the most demanding surface quality applications in flat steel, where the subsequent electrolytic tinning process requires a substrate surface free of oxide residues to ensure uniform tin deposition and coating adhesion. Residual scale entering the tinning line creates local variations in the electrochemical conditions of the plating bath, producing uneven tin coverage and potential adhesion failures that may not be detectable until the material has been further processed or has reached the customer. The consequences of under-pickling at this facility are therefore not confined to the pickling line itself but propagate through the downstream production chain to the finished product.

The speed setting for each coil in conventional operation is determined by the material grade and nominal thickness specified in the production order, with empirical correction factors accumulated from operating experience. This approach is adequate for managing the systematic differences between broad material categories but cannot respond to the coil-specific variability in scale composition and residual coverage that arises within each category. The result is a persistent gap between the speed at which the line operates and the speed it could support if the actual scale condition of the material were directly measured and continuously tracked.

Scale as an area-based phenomenon: why event-based inspection is structurally inadequate



Surface defects in flat steel production are conventionally characterised as discrete events: a dent at a defined position on the strip, an abrasion of specified length and depth, a shell defect of measured lateral extent. This event-based representation is appropriate for localised topographic anomalies whose severity is determined by their individual geometric properties, depth, profile sharpness, proximity to the strip edge as established in WP4. It is inadequate for scale, whose operational significance is not a property of individual surface patches but of their collective coverage of the strip surface.

Scale distributes across the strip surface in spatial patterns that reflect the combined influence of the oxide phase composition, the acid concentration gradient along the pickling bath, and the local hydrodynamic conditions of acid-to-surface contact. In a given coil section, some regions may be fully descaled while adjacent regions retain residual oxide patches of varying density. The operationally relevant quantity is not the depth, width, or position of any individual patch but the fraction of the total strip surface area covered by residual oxide within a defined length of strip, the scale affection fraction. A section with many small scattered patches of low individual significance may have a higher affection fraction, and therefore a greater chemical treatment deficit, than a section with fewer but larger patches. The event-based paradigm, which evaluates each detection individually, cannot construct this aggregate directly from its outputs.

This structural inadequacy is compounded by the measurement characteristics of scale as a surface condition. As noted in WP1, scale produces no reliable geometric signature at the height measurement resolution available from the laser triangulation sensors of the combined 2D/3D inspection system installed at the RAS pickling line: at thicknesses of 5 to 20 micrometres, the oxide layer lies below the practical detection threshold of the three-dimensional channel under production conditions. Scale quantification depends exclusively on the two-dimensional imaging channel, which is sensitive to the reflectance contrast between oxide-covered and metallic surface regions. This contrast, as discussed in WP2 in relation to non-topographic defect inspection in wet environments, is not stable: it is modulated by liquid film thickness, illumination geometry, and surface roughness variations between material grades. The detection algorithm for scale must therefore operate robustly across a range of reflectance conditions rather than relying on a fixed contrast threshold calibrated to a single reference state.

The combination of these two constraints - the area-based nature of scale and the optical variability of its detection - defines the specific requirements for the inspection and quantification approach that the SurfConInspect speed optimisation use case must address. The approach cannot be assembled by extending the event-based infrastructure used for topographic defect monitoring. It requires a distinct computational layer, the aggregated quality index, that accumulates spatial detection results over defined windows of strip length and translates them into a scalar representation of coverage fraction suitable for input to the speed control logic.

Computing the scale affection index

The scale affection index is the output of a computation chain that starts with the binary classification of pixels in the two-dimensional inspection image as either scale-affected or scale-free, and ends with a smoothed fractional coverage estimate reported to the quality processor at a rate compatible with the dynamics of the speed control loop. The design of each stage in this chain reflects specific trade-offs between sensitivity and robustness that cannot be resolved independently of the process context in which the system operates.

Pixel classification is performed by a detection algorithm that identifies connected regions of the inspection image whose mean intensity deviates from the local background distribution by more than a defined threshold. Scale-affected regions appear as darker areas in brightfield illumination, where the iron oxide phases absorb incident light more strongly than the metallic substrate. If effective reflectance contrast between scale and bare steel is not a constant adaptive thresholding may be applied adapting the detection threshold to the current contrast level, a parameter that is monitored continuously from the background statistics of the inspection image, rather than set once during commissioning and left fixed.

Coverage aggregation transforms the binary pixel classification into a fractional coverage estimate for a defined spatial window. The window length is a design parameter that governs the balance between temporal resolution and statistical stability of the index. A short window resolves rapid transitions in scale coverage along the coil length but is sensitive to short-range fluctuations that reflect genuine local variability in the scale layer rather than changes in the overall chemical treatment adequacy. A long window produces a more stable estimate of the underlying affection level but introduces a lag between an actual change in surface condition and its reflection in the reported index, a lag that must remain shorter than the response time of the speed control system if the control loop is to be effective. At the RAS pickling line, the practical constraints on window length are set by the physical distance between the inspection zone and the point on the line at which a speed change takes mechanical effect, which defines the minimum useful control lag.

Smoothing of successive window estimates further stabilises the index against measurement noise and short-range surface variability. The filter bandwidth is selected jointly with the window length so that the combined frequency response of the aggregation and smoothing stages matches the dynamic requirements of the speed control application: fast enough to detect genuine trends in scale affection as they develop along the coil, slow enough to suppress fluctuations that would generate unnecessary control actions. The resulting index is a continuous, strip-position-referenced signal whose value represents the fractional coverage of residual oxide in the most recent inspection window, updated at each new window as the strip advances through the inspection zone.

The physical basis for speed control via scale affection

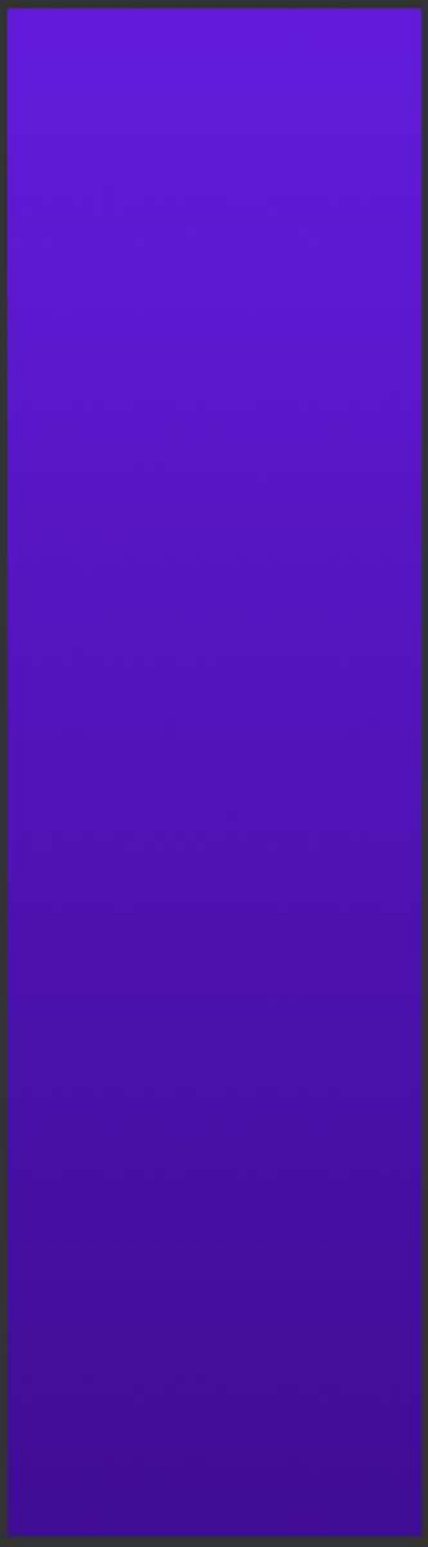
The use of scale affection as an input to speed control rests on a well-characterised physical relationship: the amount of oxide dissolved during the transit of a strip section through the pickling bath is proportional to the product of the dissolution rate and the residence time, and the residence time is inversely proportional to the strip speed. This proportionality holds under the kinetically controlled dissolution conditions that prevail in modern turbulent-flow horizontal pickling tanks, where acid transport to the strip surface is rapid relative to the rate of the dissolution reactions and the overall process rate is therefore determined by the surface chemistry rather than by diffusion. Under these conditions, a ten percent increase in strip speed reduces the residence time by approximately ten percent, which reduces the oxide dissolved in the bath by approximately the same fraction, all else equal. Conversely, a reduction in speed increases dissolution proportionally.



The scale affection index measured at the inspection zone reflects the oxide coverage remaining on the strip after partial dissolution in the upstream sections of the bath. A high index value, indicating that a significant fraction of the strip surface remains oxide-covered, means that the current speed has not provided sufficient residence time for the dissolution reactions to go to completion. The strip is exiting the bath with a chemical treatment deficit. A low index value, indicating that the oxide has been substantially removed well before the strip reaches the inspection point, means that the current speed is more conservative than the scale characteristics of the material require, and that the residence time could be reduced without compromising the completeness of pickling. In both cases, the index provides the information needed to adjust the speed toward the value that matches the actual dissolution requirements of the coil section currently under the inspection system.

The relationship between index value and the magnitude of the required speed adjustment is not determined by the index alone. It depends on the acid concentration and temperature profile along the bath at the moment of measurement - process conditions that may change independently of the strip surface condition - and on the position of the inspection zone relative to the exit of the pickling bath, which determines what fraction of the total dissolution has already occurred by the time the index is computed. These upstream process parameters are available from the line's process control system and are incorporated into the quality model of the scale affection processor, which maps the current index value and process state to a recommended speed adjustment rather than applying a fixed index-to-speed conversion.
The quality model requires calibration to the specific geometry and process conditions of the pickling line. At the RAS Andernach installation, this calibration draws on the historical database of coil-level scale affection records and downstream surface quality outcomes accumulated by the ASIS over its operational history, the kind of process-specific knowledge asset that has been identified as a primary enabler of data-driven quality optimisation in flat steel production. The availability of this historical data is one of the factors that makes the RAS facility a well-suited site for the development and validation of the speed optimisation use case within SurfConInspect.

Aggregated indices and the broader quality control architecture



The aggregated quality index concept extends the event-based quality assessment paradigm that has historically dominated ASIS in flat steel production. In an event-based system - adequate for the topographic defect monitoring described in WP4 and WP7 - the primary output of inspection is a list of discrete events, each evaluated individually against severity thresholds. For distributed surface phenomena like scale, individual event severity is not the operationally relevant quantity: what matters is the cumulative spatial extent of a surface condition across a defined area of the strip, a quantity that is not accessible from a list of events without an explicit aggregation step.

As described in WP6, the quality processor architecture of SurfConInspect supports the concurrent operation of multiple processors, each monitoring a distinct quality aspect and generating quality events that are forwarded to the online quality supervisor. The scale affection processor is one instance of this architecture; the cutting control processor for topographic heavy defects is another; the online grading processors at the RAS tinning line and the SZFG electrolytic galvanising line are two further instances. All four share the same structural logic, a quality model that maps inspection data to a quality index, a threshold structure that triggers quality events, and an interface to the supervisory layer, but each implements this logic with parameters and aggregation methods appropriate to the specific physical quantity it monitors. For scale affection, the aggregation method is fractional coverage estimation over spatial windows, as described in the preceding section. For topographic defect severity, the aggregation is different: the quality processor accumulates the severity scores of individual events, weighted by their near-edge proximity factor, and computes a risk index for the current coil section. For online grading at finishing lines, the aggregation combines multiple quality dimensions - surface defect density, classification distribution, positional statistics - into composite indices that support grade assignment decisions. The variety of aggregation methods across these use cases reflects the physical diversity of the quality aspects being monitored, and the common architectural framework that hosts them is what makes it possible to manage this diversity within a coherent, operationally integrated quality control system.

The interaction between the scale affection processor and the cutting control processor, both operating on the same coil at the RAS pickling line, illustrates a property of the architecture that is not apparent from considering either processor in isolation. When the cutting control processor triggers a cut that physically removes a section of the coil, the length of strip available for scale affection aggregation changes: the window that was accumulating coverage data from the removed section must be reset or adjusted to reflect the modified coil geometry. The online quality supervisor maintains a coherent accounting of the coil geometry across cutting events and communicates this to the active processors, ensuring that neither quality index is computed over strip lengths that no longer correspond to the physical coil. This coordination function is one of the reasons why the supervisory layer in WP6 is not a passive relay between processors and control systems but an active component of the quality control architecture.

Speed control logic and integration with the online quality supervisor

The translation of the scale affection index into a speed adjustment is performed by the online quality supervisor, which receives quality events from the scale affection processor and maps them to speed signals directed at the pickling-line drive system. The response structure is tiered: index values below a lower threshold trigger a speed increase recommendation, index values above an upper threshold trigger a speed reduction, and values within the band between the two thresholds indicate that the current speed is appropriate and no adjustment is needed. The width of this band reflects the desired sensitivity of the control system, a narrow band produces more frequent, finer-grained adjustments that track the actual scale condition closely; a wide band reduces control activity and is more tolerant of index fluctuations.

Speed adjustment signals are subject to rate constraints imposed by the mechanical characteristics of the line drive system. The maximum permitted rate of speed change - expressed as a fraction of nominal speed per unit of strip length - prevents abrupt transitions that could cause strip tension instability or mechanical disturbances at the entry or exit sections of the line. These constraints introduce an effective lag between the detection of a scale condition that warrants a speed change and the completion of that change, which must be accounted for in the design of the threshold logic to avoid oscillatory behaviour in which the control system overshoots and then corrects repeatedly.

As established in WP6 for the quality control architecture in general, the online quality supervisor supports both automatic and human-assisted control modes. For scale affection, the appropriate mode depends on the clarity of the index signal: when the index is unambiguously above or below the threshold band, automatic speed adjustment is appropriate, since the evidence is clear and the delay from seeking operator confirmation would reduce the effectiveness of the intervention. When the index is near a threshold boundary, a situation that can arise during coil transitions, where the scale characteristics of successive coils differ, human supervisory control is more appropriate. In this case, the supervisor presents the recommended speed adjustment to the operator alongside the current index value and recent trend, and the operator confirms or overrides the recommendation based on contextual knowledge of the production situation that the index alone does not capture.

This balance between automatic and human control is not a fixed configuration but a parameter of the system that can be adjusted during commissioning to reflect the operational priorities and risk tolerance of the production facility. At the RAS Andernach installation, where the consequences of under-pickling extend to downstream tin-plate quality as described in section one, a relatively conservative automatic control configuration with wider threshold bands and a preference for human confirmation in borderline cases, is appropriate during the initial operational phase, with progressive automation as the reliability of the index is validated through the longitudinal performance monitoring described in WP6.

Industrial context and performance expectations

The scale affection speed control use case is implemented at the RAS pickling line in Andernach, which processes hot-rolled coils for tin-plate production at throughput levels that make pickling-line capacity a constraint on overall production output during peak demand periods. The facility has operated automatic surface inspection systems for an extended period, accumulating a substantial historical database of coil-level inspection records alongside downstream quality outcomes. This operational history provides the empirical foundation for the quality model calibration described in section four and a baseline against which the performance of the speed optimisation system can be evaluated.



The one percent yield improvement target defined in the SurfConInspect project plan translates, at the throughput levels of the RAS Andernach facility, into a material quantity of additional production capacity made available without capital investment in line equipment. The mechanism is straightforward: coils currently processed at conservative speeds because their material grade places them in a slow-speed category can be processed faster when real-time scale affection measurement confirms that their actual oxide coverage is lower than the category worst-case assumption. The productivity gain is proportional to the frequency with which actual scale affection falls below the worst-case assumption, a frequency that can be estimated from the historical inspection record and that defines the realistic potential for improvement.

The one percent figure is a project-level estimate based on analysis of the RAS historical data and calibrated to the specific material mix and process conditions of the facility. Its realisation in production depends on the accuracy of the scale affection index under real operating conditions and the stability of the speed control response structure over the range of coil types and process states encountered in continuous operation. The SurfConInspect industrial demonstration phase includes provisions for iterative refinement of the index computation parameters and the control logic thresholds based on operational feedback from the RAS production team and the longitudinal performance data generated by the traceability record of the quality processor architecture.

A further dimension of the expected performance impact concerns the reduction of under-pickling incidents, cases where residual scale on the strip entering downstream processes generates quality deviations or process disturbances. Under the conservative speed management regime currently in place, under-pickling incidents are rare but not absent: they occur precisely in the cases where a coil's actual scale characteristics are more demanding than the material grade assumption allows. With real-time scale affection monitoring, speed can be reduced proactively when the index rises above the threshold, intercepting these cases before they progress to downstream processing. The reduction in under-pickling incidents represents a quality benefit that is independent of the productivity improvement and that contributes to the overall value case for the speed optimisation use case within the SurfConInspect project.

The SurfConInspect perspective

The scale affection speed control use case occupies a distinctive position within the SurfConInspect project because it demonstrates that surface inspection data can contribute to process optimisation, not only quality protection. The cutting control use case described in WP6, like the grading applications at the RAS tinning line and the SZFG electrolytic galvanising line, uses inspection results to detect and respond to quality deviations that have already occurred in the material. The speed optimisation use case uses inspection results to adapt the process in real time to the actual surface condition of the material, reducing the frequency with which quality deviations occur downstream. The distinction is between reactive quality control and proactive process optimisation, a distinction that the SurfConInspect quality control architecture is specifically designed to support through its modular processor framework.

Within this framework, the scale affection processor and the cutting control processor are the two quality processors active at the RAS pickling line, operating in parallel on the output of the same combined 2D/3D inspection system and reporting their respective quality events to the same online quality supervisor. The fact that both processors can coexist and operate independently on the same data stream, without interference or coupling between their quality models, validates the modularity of the architecture described in WP6. Each processor addresses a physically distinct quality aspect, uses the appropriate channel of the inspection data for its specific measurement task, and generates quality events whose combined interpretation by the supervisor produces a more complete and operationally coherent picture of coil surface quality than either processor could provide alone.

The open data initiative developed within SurfConInspect includes scale-related surface conditions among the image categories represented in the shared dataset. By providing labelled examples of scale coverage at different affection levels and under varying optical conditions, the dataset contributes to the broader research community's ability to develop and benchmark scale detection algorithms for continuous industrial inspection, a category of inspection problem that has received less systematic attention in the academic literature than localised defect detection, despite the direct relevance of scale coverage quantification to the process control applications described in this paper.

The integration of the scale affection use case within the SurfConInspect framework also illustrates the role that process physics plays in the design of effective quality control systems. The aggregated index approach and the process-model-based speed control logic are not generic solutions imported from a different application domain; they are engineering choices grounded in the specific physical properties of oxide dissolution, optical contrast under wet conditions, and pickling-line process dynamics. This grounding in process physics is the characteristic that distinguishes the SurfConInspect approach to quality control from generic data-driven approaches, and that gives its industrial implementations the specificity required to meet the quantitative performance targets defined in the project plan.

Conclusions

Scale affection is the surface quantity that governs the adequacy of pickling treatment at any given combination of acid conditions and strip speed. Its variability, driven by differences in hot rolling thermal history, oxide phase composition, and coil geometry, means that a single conservative speed setting cannot be simultaneously optimal for all material processed on a pickling line. The productivity cost of this conservatism is systematic and proportional to the frequency with which actual scale affection falls below the worst-case grade assumption that current speed settings reflect.



Real-time quantification of scale affection through the two-dimensional inspection channel of the combined 2D/3D system installed at the RAS pickling line provides the measurement basis for closing this gap. Scale is an area-based phenomenon whose operational significance is determined by the fractional coverage of residual oxide over a defined strip length, not by the properties of individual scale patches. The aggregated quality index, computed by accumulating pixel-level coverage data over spatial windows and smoothing the result to match the dynamics of the speed control application, provides a scalar representation of this coverage fraction that is directly usable as an input to the speed control logic of the online quality supervisor.

The physical basis for the speed control strategy is the inverse relationship between strip speed and acid residence time, which under kinetically controlled dissolution conditions determines the total oxide removed per unit length of strip. An index value above the threshold band indicates a chemical treatment deficit at the current speed; an index value below it indicates that the current speed is more conservative than the material requires. The online quality supervisor responds to these signals by generating speed adjustment recommendations, automatic for clear threshold crossings, human-assisted for borderline cases, subject to the rate constraints of the line drive system.

Within the broader SurfConInspect quality control architecture, the scale affection processor operates in parallel with the topographic defect processor on the same inspection data stream and reports to the same online quality supervisor. This parallel operation, enabled by the modular architecture described in WP6, allows the two use cases at the RAS pickling line, cutting control and speed optimisation, to be managed concurrently within a single quality control framework without coupling or interference between their respective control logics. The validated performance of this architecture under real production conditions at the RAS Andernach facility constitutes one of the central contributions of the SurfConInspect project to the advancement of surface quality management in European flat steel production.

SURF CON INSPECT

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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