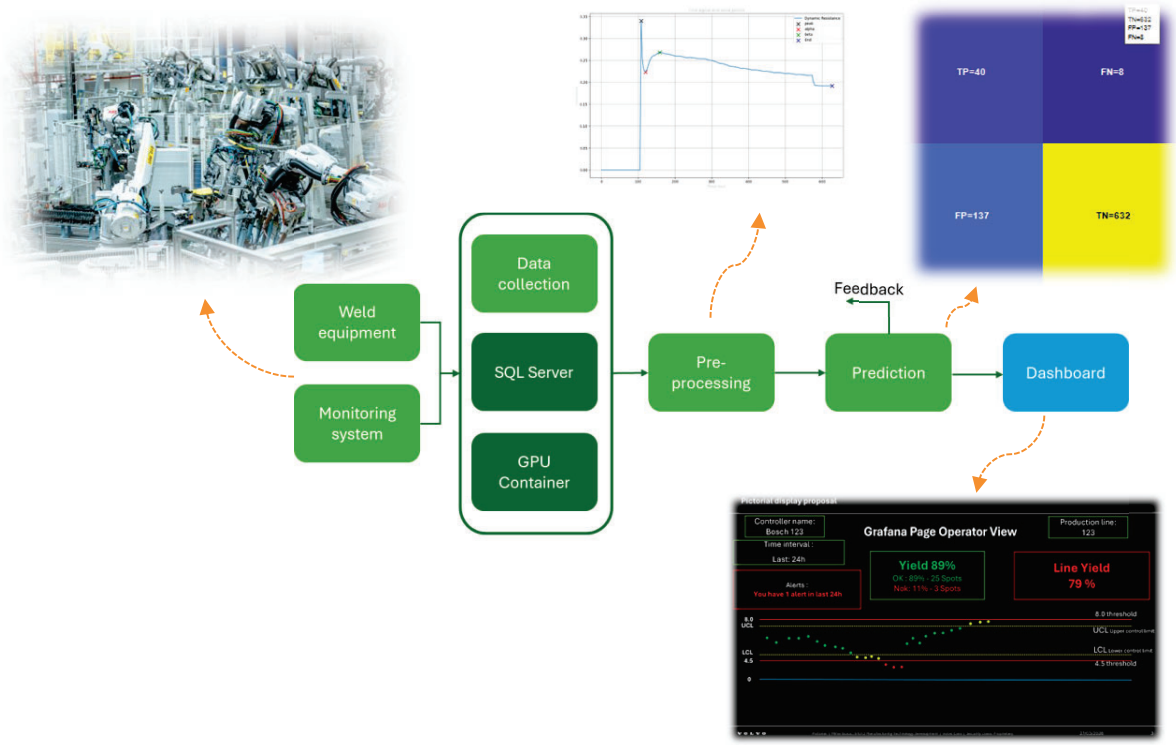
PICTORIAL

Predictive Intelligent Control for Resistance Welding

Public report

Project within FFI Circularity
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Fordonsstrategisk Forskning och Innovation

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FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

For more information: www.ffisweden.se

1. Summary

The PICTORIAL project has during its run time August-23 to March-26 investigated how machine learning can be applied for predictive quality monitoring of resistance spot welding (RSW) in industrial production. The motivation was the increasing challenge of ensuring robust weld quality as advanced and more sustainable materials are introduced in automotive manufacturing, while traditional quality control methods remain reactive, costly, and largely destructive.

The project developed and evaluated data-driven models trained on real production data from welding controllers. By combining welding domain knowledge (i.e. established understanding of welding processes, materials, and production variability) with machine-learning methods, the project demonstrated that weld quality indicators such as nugget diameter can be predicted with stable performance within defined operating conditions.

Key methodological contributions include causal feature selection, meaning that only process signals that showed a direct physical influence on weld quality were used, and Fuzzy Information Granulation (FIG), which is a method for summarising noisy production data over multiple welds to improve robustness. A probability-based quality assessment was applied on top of the nugget diameter predictions to support explicit handling of decision risk.

In addition to model development, the project implemented and tested a demonstrator system with role-adapted dashboards for operators, engineers, and production management. This enabled real-time monitoring, early detection of quality drift, and reduced reliance on destructive testing. The implementation was done at one of the participating manufacturers and was intended as a pilot-like deployment rather than a full production rollout.

The results show that AI-based weld quality monitoring is feasible and industrially relevant when trained on representative production data and combined with explicit risk handling. At the same time, the project clearly identifies limitations related to class imbalance –specifically the fact that defective welds can be very rare in high-quality production, making learning and validation more challenging, changes in production conditions not reflected in the training data, and restricted access to dynamic weld process signals. Overall, PICTORIAL contributes to increased process robustness, improved digital maturity, and improved possibilities for sustainable manufacturing.

2. Sammanfattning

PICTORIAL-projektet har under sin löptid augusti-23 till mars-26 undersökt hur maskininlärning kan användas för prediktiv kvalitetsövervakning av motståndspunktsvetsning i industriell produktion. Bakgrunden är ökade krav på robust svetskvalitet i takt med införandet av avancerade och mer hållbara material, samtidigt som traditionella kvalitetsmetoder i huvudsak är reaktiva och destruktiva.

Projektet visar att det är möjligt att använda befintliga produktionsdata från svetsstyrsystem för att kunna prediktera erhållen svetskvalitet och även identifiera en kvalitetsdrift över tid. Genom att kombinera svetsdomänkunskap (praktisk och teoretisk kunskap om svetsprocesser, material och produktionsvariationer) med datadrivna metoder har stabila modeller utvecklats för definierade produktionsförhållanden. Centrala metodinslag är ”causal feature”-selektion, vilket innebär att endast signaler med direkt påverkan på svetskvaliteten används, samt Fuzzy Information Granulation (FIG) där flera efterföljande svetsar sammanfattas för att minska brus och öka robustheten i produktionsdata. Detta kompletteras med sannolikhetsbaserad kvalitetsbedömning, som ger tydligare riskhantering i produktion.

Arbetet har genomförts i en sekventiell och produktionsnära arbetsgång, där verkliga produktionsdata först samlades in och strukturerades, därefter kopplades till uppmätta kvalitetsmått och slutligen användes för modellutveckling och utvärdering. Parallellt med dataarbetet genomfördes workshops med representanter för olika yrkesroller, såsom operatörer, produktionstekniker, svets- och kvalitetsingenjörer och ledning, för att gemensamt definiera hur produktionsdata kan extraheras i praktiken och hur resultaten ska presenteras på ett ändamålsenligt sätt för olika användargrupper.

De framtagna modellerna har integrerats i ett demonstratorsystem med rollanpassad visualisering och testats i en industrilik produktionsmiljö hos en av de deltagande tillverkarna, med verkliga produktionsdata. Demonstratorn användes för utvärdering, lärande och identifiering av praktiska begränsningar. Mer arbete kring datauttag och hantering behövs innan en fullskalig produktionsimplementation kan ske.

Projektet tydliggör viktiga begränsningar kopplade till databalans, förändrade produktionsförutsättningar och tillgång till dynamiska signaler. Dessa erfarenheter utgör ett viktigt underlag för fortsatt utveckling och framtida industriell implementering.

Sammanfattningsvis demonstrerar PICTORIAL hur AI-baserad kvalitetsövervakning kan införas på ett realistiskt och ansvarsfullt sätt i industrin, samt de åtgärder som behöver vidtas för att nå implementering. Projektet och dess resultat är helt i linje med FFI Cirkularitets mål om en hållbar, resurseffektiv och digitaliserad produktion.

3. Background

Resistance spot welding is a core joining process in the automotive industry, with thousands of welds performed per vehicle. Increasing use of advanced high-strength steels, new coatings, and lightweight materials places higher demands on process robustness and quality assurance. At the same time, conventional quality control relies heavily on post-process inspection and destructive testing, which limits early detection of quality drift and increases resource consumption.

Digitalization and data availability in modern welding equipment provide new opportunities to improve quality monitoring. However, applying machine learning in production welding requires methods that can handle noisy, imbalanced, and variable industrial data. PICTORIAL addresses this need within the FFI Circularity programme by focusing on possibilities to develop applicable and robust AI-based quality monitoring using real production data.

4. Purpose, research questions and method

The purpose of the project was to evaluate whether machine-learning methods can be used for reliable, predictive weld quality monitoring in largescale industrial RSW production.
The main research questions were:

- Can real production data from welding controllers be used to predict weld quality with sufficient robustness?
- How can domain knowledge be combined with data-driven methods to improve model stability?
- How can decision risk be handled explicitly in production environments with strong class imbalance?

The project followed a sequential, production-driven methodology. First, real production data were collected from welding controllers in industrial environments and analysed to understand natural process variation. The data were then cleaned, structured, and linked to measured quality outcomes, correct nugget diameter in this case.

In the next step, relevant process signals were selected based on welding domain knowledge and causal relationships to weld quality. These signals were used to train and evaluate machine-learning models for quality prediction and monitoring. Finally, the developed models were integrated into a demonstrator system and tested in an industrial-like production environment to evaluate practical usability and limitations.

In parallel with the data-driven work, workshops were conducted with representatives from different professional roles, including operators, production engineers, quality engineers, and management. These workshops were used to define how production data could practically be extracted and interpreted, and how the results from the developed models should be presented in a way that is meaningful for different user groups.

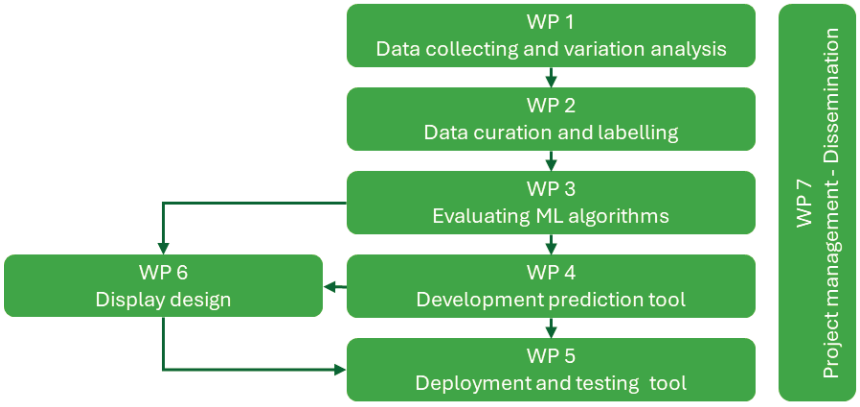


Figure 1. Illustration of work packages and their interaction in the project.

The final models were evaluated using both regression and probability-based performance metrics and tested in production-like environments using a demonstrator system, and predictions from the demonstrator system were compared to available results from destructive testing (tear-down, used as reference quality measures).

An illustration of the project workflow is shown in Figure 2 below.

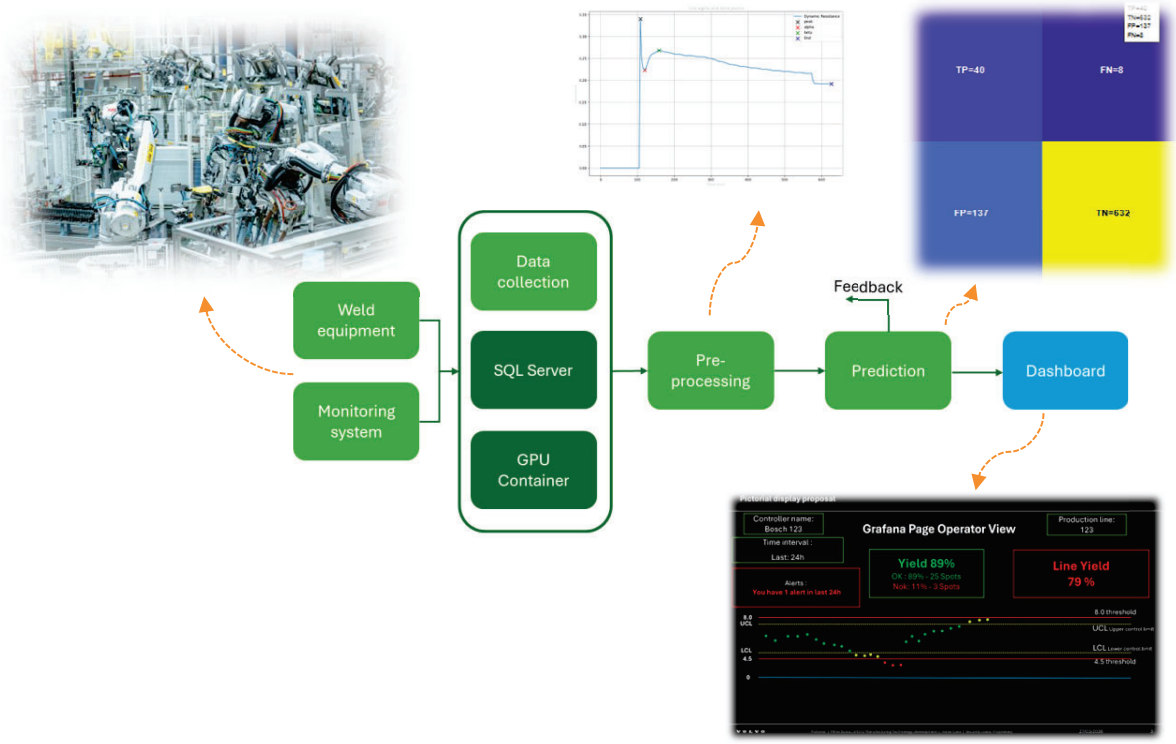


Figure 2. Illustration of the workflow in the project.

5. Objective

The objective for the PICTORIAL project was to develop a predictive, intelligent quality monitoring system for resistance spot welding (RSW) based on machine learning models trained on real production data. The overall aim was to provide cognitive support to operators, engineers, and quality personnel by predicting weld quality, detecting quality drift at an early stage, and enabling corrective actions before defects occur.
In bullets, the project objectives were:

- Developing a non-destructive, inline estimation and monitoring system for weld quality indicators such as weld nugget diameter.
- Curating and using real production data from automotive factories rather than from laboratory trials or simulated data, in order to ensure industrial relevance and robustness.
- Combining welding domain knowledge and data science to improve model stability, interpretability, and applicability in production environments.
- Using the model to support increased weld process robustness with respect to material combinations - helping the introduction of advanced and more sustainable materials (e.g. AHSS, aluminium, fossil-free and scrap-based materials).
- Contributing to social sustainability throughout the value chain by providing cognitive support that improves working conditions, reduces manual inspection effort, and supports informed human decision making (mission 2b of the Circularity sub programme).
- Strengthening digitalisation and competence development in welding production through collaboration between industry, research institutes, and academia.

These objectives have remained fundamentally unchanged throughout the project, however, as the project progressed and insights were gained from working with real production data, the focus was refined in certain areas. In particular, increased emphasis was placed on:

- Probability based quality assessment, rather than purely deterministic OK/NOK classification or absolute nugget diameter predictions, to better reflect industrial decision making under strong class imbalance.
- Explicit handling of decision risk, especially the tradeoff between missed defective welds and conservative warnings.

Identifying and documenting limitations related to changes in production conditions and data representativeness, based on observations made during deployment-like testing in an industrial environment.

These refinements did not represent a change in objectives, but rather a deepening and operationalisation of the original goals, ensuring that the developed solution remains realistic, transparent, and applicable under real production conditions.

Overall, the project has pursued the objectives described in the application and aligned them closely with the intent of the FFI Circularity programme, contributing to more robust, resource efficient, and socially sustainable manufacturing.

6. Results and deliverables

The PICTORIAL project has delivered both methodological and practical results that contribute to the objectives of the FFI programme, and to the Circularity programme in particular. In selected test scenarios, the developed algorithms demonstrated a high ability to identify non-acceptable welds, with a weld diameter prediction R^2 score of approximately 90 %, and classification scores of 17% false negatives and 18% false positives in selected test scenarios. These results were achieved using the data available within the project, which were limited in size, strongly imbalanced, and mainly based on static per-weld signals. These results indicate that the proposed approach is feasible under realistic industrial data conditions.

The project also identified clear potential for further improvement through access to more dynamic welding signals and improved system integration. In addition, analysing sequences of consecutive spot welds, rather than individual welds only, was identified as a promising approach to increase predictability, even when primarily static data are used.

Contribution to FFI programme objectives

In line with FFI's overall effect goals, the project has demonstrated a solution that supports more robust, efficient, and sustainable manufacturing processes in the automotive industry. By enabling predictive quality monitoring based on real production data, the project contributes to increased process stability, reduced scrap, and reduced need for reliance on destructive testing. This supports FFI's ambition to demonstrate solutions that enable fossil-free, safe, and efficient transport systems through improved manufacturing quality and resource efficiency in manufacturing.

The project has also contributed to FFI's goal of strengthening competence, infrastructure, and collaboration within the Swedish automotive ecosystem. Through close cooperation between industry, research institutes, and academia, the project has built shared understanding of how AI-based methods can be successfully and responsibly applied in production environment.

Contribution to the Circularity sub-programme

The results of PICTORIAL directly address several focus areas within the Circularity programme:

- **Climate-neutral, circular manufacturing:**
  By reducing scrap rates, rework, and unnecessary destructive testing, the project supports reduced material- and energy consumption in welding production. Improved process robustness also enables more efficient use of advanced and recycled materials, which are often more sensitive to process variation.
- **Resource efficiency across the value chain:**
  Predictive monitoring allows earlier detection of quality drift, reducing

downstream quality losses and unnecessary use of components and materials. This contributes to a more efficient use of resources throughout the manufacturing phase of the vehicle.

- **Social sustainability and cognitive support:**
  The project delivered a role-adapted demonstrator with dashboards tailored for operators, engineers, and production management. This provides cognitive support rather than automation of decision-making, improving working conditions by reducing manual inspection effort and supporting informed human decisions in production.

Key project deliverables

The main deliverables of the project include:

- A validated machine-learning framework for predictive weld quality monitoring based on real production data from resistance spot welding.
- Integration of causal feature selection and Fuzzy Information Granulation (FIG) to improve robustness and stability under industrial variability.
- A probability-based quality assessment approach enabling explicit handling of decision risk under strong class imbalance, which is typical for high-quality production environments.
- A demonstrator system with role-adapted visualisation supporting operators, engineers, and production management.
- Documented insights into limitations related to class imbalance, domain shift, and restricted access to dynamic process signals.
- Internal project report.
- Public project report (PICTORIAL).
- Conference presentation.
- Research papers (2 pending).

Goal fulfilment and deviations

The project has largely fulfilled its stated objectives. It has demonstrated the feasibility and industrial relevance of AI-based weld quality monitoring using real production data, in line with the intent of the FFI Circularity programme.

One identified limitation was the restricted availability of defective weld data (data for non-approved welds), which constrained the achievable performance for defect classification. This limitation is representative of real production conditions and has therefore provided valuable insight into requirements for future implementation rather than constituting a negative deviation. No major deviations from the original project plan occurred, except a prolonged time schedule due to strategic changes in some of the participating companies, and connected revision of budget. The extra time enabled increased possibilities to gather more data.

Overall contribution

Overall, PICTORIAL contributes to the FFI programme by providing a realistic and applicable example of how digitalisation and AI can be used to support circular manufacturing, resource efficiency, and social sustainability in the automotive industry. The project clarifies both the potential and the prerequisites for industrial deployment, thereby supporting informed future investments and continued research within FFI.

7. Dissemination and publications

Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	x	Industrial partners and research organisations
Be passed on to other advanced technological development projects	x	Input to future FFI and industrial R&D projects
Be passed on to product development projects	x	Basis for future industrial implementation
Introduced on the market		Requires further development
Used in investigations / regulatory / licensing / political decisions		Not applicable

The project results are linked to ongoing and planned activities within welding digitalisation and AI-based manufacturing. At least one of the participating industrial partners plans to continue evaluating the developed methods for potential implementation in its own production environment. For another industrial partner, the project results align directly with the company's long-term roadmap for increased digitalisation of manufacturing and quality monitoring processes.

In addition, RISE has used PICTORIAL as an illustrative example in related research activities addressing data handling and data security in the context of advanced manufacturing systems, thereby extending the impact of the project beyond welding applications.

The project and its results have been presented at Fogningsdagarna, the annual joining conference arranged by the Swedish Welding Commission. Two internal project disseminations have also been arranged.

Publications

- Public project report (PICTORIAL).
- Internal project report.
- Technical article in Svetsen.
- 2 scientific publications related to machine learning in welding:
    - *Causal Feature Selection and Fuzzy Information Granulation for Quality Prediction in Resistance Spot Welding (Dan et al.).*
    - *From Quality Prediction to Bad-Weld Warning: A Hierarchical Probabilistic Framework for Imbalanced Resistance Spot Welding Data (Dan et al.).*

8. Conclusions and future research

In summary, the algorithms developed in PICTORIAL demonstrated the capability to identify non-acceptable welds in targeted evaluation cases, with high prediction performance for the required minimum sized weld nugget diameters. These results were achieved using the available project data, which were limited in size, strongly imbalanced, and based on static and averaged weld process signals.

The project also identified clear directions for further improvement. In particular, access to more dynamic welding data and improved system integration are expected to enhance prediction robustness. In addition, extending the analysis to include contextual information such as trends from sequences of consecutive spot welds, rather than evaluating each weld in isolation, was identified as a promising approach to further strengthen decision support in production. These findings form an important basis for continued development beyond the project.

The project concludes that AI-based weld quality monitoring using real production data is feasible and valuable when combined with domain knowledge, calibrated probability estimates, and explicit risk handling. The results support reduced reliance on destructive testing and improved process robustness. AI-based weld quality monitoring will also support a continued implementation of thinner and more advanced metallic materials in car body design and production.

Future research should focus on:

- Integration of dynamic signals from the welding process.
- Targeted collection of defective (non-approved) and borderline weld data.
- Development of out-of-distribution detection.
- Generalizable models using transfer and incremental learning.

The project thereby provides both a practical example and a knowledge base for continued implementation of AI-based quality monitoring within the FFI Circularity programme.

9. Participating parties and contact persons

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Participating organisations

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Volvo Car Corporation (VCC) / Volvo Personvagnar AB
RISE Research Institutes of Sweden AB
KTH Royal Institute of Technology
Gestamp HardTech AB
ArcelorMittal
Svetsrådet i Stockholm AB
Modul-System HH AB