RE4DY

MANUFACTURING DATA NETWORKS

Title	Industrial pilot area validation & pilot benchmark and KPIs_Process Operations
Document Owners	UNINOVA
Contributors	VWAE, AVL, FILL, VIS, CEIT
Dissemination	PUBLIC
Date	30.09.2025
Version	V1

Table of contents

Document Status

Leader	UNINOVA
Internal Reviewer 1	INNO
Internal Reviewer 2	SIEMENS
Work Package	WP4
Deliverable	D4.3 Industrial pilot area validation & pilot benchmark and KPIs_Process Operations
Due Date	M40
Delivery Date	30/09/2025
Version	V1

Version History

0.1	UNINOVA: ToC
0.2	UNINOVA: Section 4
0.3	VWAE: Section 2
0.4	AVL: Section 3
0.5	UNINOVA: Consolidation
0.6	VWAE: Section 2, Section 4 refinement
0.7	AVL: Section 3, Section 4 refinement
0.8	UNINOVA: Introduction, Conclusion, Annex
0.9	Internal review: ALL
1.0	Final updates: AVL, VWAE

Further Information

More information about the project can be found on project website: https://re4dy.eu/

Disclaimer

The views represented in this document only reflect the views of the authors and not the views of the European Union. The European Union is not liable for any use that may be made of the information contained in this document.

Furthermore, the information is provided "as is" and no guarantee or warranty is given that the information is fit for any particular purpose. The user of the information uses it at its sole risk and liability.

Project Partners

Number	Participant organisation name	Acronym
1	ASOCIACIÓN DE EMPRESAS TECNOLÓGICAS INNOVALIA	INNO
1.1	CBT COMUNICACION & MULTIMEDIA SL	CBT
2	CHALMERS TEKNISKA HOGSKOLA AB	Chalmers
3	INTERNATIONAL DATA SPACES EV	IDSA
4	VOLKSWAGEN AUTOEUROPA, LDA	VWAE
5	ASSECO CEIT AS	CEIT
6	UNINOVA-INSTITUTO DE DESENVOLVIMENTO DE NOVAS TECNOLOGIAS-ASSOSIACAO	UNI
7	FILL GESELLSCHAFT MBH	FILL
8	AVL LIST GMBH	AVL
9	VISUAL COMPONENTS OY	VIS
10	UNIVERSIDAD MIGUEL HERNANDEZ DE ELCHE	UMH
11	ATLANTIS ENGINEERING AE	ATLANTIS
12	DATAPIXEL SL	DATA
13	CORE KENTRO KAINOTOMIAS AMKE	CORE
14	UNIVERSITETE I OSLO	UiO
15	GE AVIO	AVIO
16	ENGINEERING-INGENIERIA INFORMATICA SPA	ENG
17	POLITECNICO DI MILANO	POLIMI
18	ATOS IT SOLUTIONS AND SERVICES IBERIA SL	ATOS IT
18.1	ATOS SPAIN SA	ATOS ES
19	KATHOLIEKE UNIVERSITEIT LEUVEN	KU
20	NETCOMPANY-INTRASOFT SA	INTRA
21	NOVA ID FCT - ASSOCIACAO PARA A INOVACAO E DESENVOLVIMENTO DA FCT	NOVA
22	INDUSTRY COMMONS FOUNDATION (INSAMLINGSSTIFTELSE)	ICF
23	ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS	CERTH
24	GRUPO S 21SEC GESTION SA	S21SEC
25	UNIVERSITAT POLITECNICA DE VALENCIA	UPV
26	CONSIGLIO NAZIONALE DELLE RICERCHE	CNR
27	SOCIEDAD ANDALUZA PARA EL DESARROLLO DE LAS TELECOMUNICACIONES SA	SANDETEL
28	SWITZERLAND INNOVATION PARK BIEL/BIENNE AG	SSF
29	GF MACHINING SOLUTIONS AG	GFMS ADVMAN
30	FRAISA SA	Fraisa SA
31	SIEMENS SCHWEIZ AG	SIE
32	MIRAITEK SRL	MIR

Executive Summary

This deliverable consolidates end-of-project evidence for two RE4DY pilots, Volkswagen Autoeuropa (VWAE) and AVL, covering full-scale implementations, industrial trials, and KPI monitoring under the RE4DY reference architecture.

This deliverable complements D5.3 by covering a different subset of pilots within the RE4DY programme. While D5.3 documented progress and outcomes from one set of industrial partners, D4.3 consolidates end-of-project evidence, operational impacts, lessons learned, and KPI results for the pilots in scope here. Together, these deliverables provide a complete view of RE4DY's cross-sector implementation and allow comparison of architectural patterns, data integration approaches, and performance outcomes across multiple contexts.

At VWAE, the final architecture combines CEIT's digital twin for scenario simulation with GT-Process automation, e-paper shop-floor updates, and targeted UNINOVA's RTLS tracking of line-feeding assets, all tied together through harmonised data connectors and a reporting layer that unifies plan–do–check across planning efficiency, asset utilisation and response time. Industrial trials validated three business processes, Autonomous Planning, Shop-floor Implementation, and Resource Optimisation, by hardening ETL and dashboards, proving remote e-paper updates, and using RTLS to compare planned versus actual flows. Early results show measurable gains in cost efficiency, planning agility and process digitalisation, with lessons centring on data harmonisation (including an AWS connection), phased change management, and pragmatic RTLS deployment where it yields the most insight.

At AVL, the architecture is built around a Visual Components-based digital twin of the Battery Innovation Center, extended with RE4DY-aligned plugins: CAD/3DXML-driven auto-setup, a resiliency check for manufacturability, SQL-server integration to reflect real shop-floor events, robotic-energy optimisation with CO_2 calculation, human-resource simulation, and data nodes for cost/energy tracking. Trials show the approach accelerates design-to-production cycles, improves planning accuracy, and strengthens energy visibility for forthcoming battery-passport obligations; remaining work focuses on usability, data quality and sustained validation where prototype variability limits long-run statistics.

KPI monitoring follows the 6Ps Performance pillar: rather than only asking whether values improved, it assesses how indicators are defined, measured, and governed across Operational/Technical, Economic, Environmental, Social, Product-Service Lifecycle and Supply-Chain areas. For both pilots, this lens, applied through structured surveys and end-phase interviews, confirms progress in digital-continuity foundations, data capture and simulation-driven decision-making, while identifying clear next steps: standardise data models and interfaces, document component-to-layer mappings, strengthen data-quality checks and reference datasets, and scale what is already working before widening the scope of AI/federated learning.

In summary, VWAE demonstrates a repeatable, twin-centred workflow that connects planning automation to shop-floor execution with tangible cost and agility benefits; AVL demonstrates a production-simulation backbone that pulls manufacturability and energy analysis earlier into design and planning. Both pilots show that robust data foundations, pragmatic integration and user-centred rollout are the decisive enablers of KPI impact and portability across the RE4DY value network.

1 Introduction

1.1 Context and scope of this document

This document reports the industrial pilot area validation of work package five of RE4DY project. The full scale-up implementation of the industrial pilots (VWAE and AVL) has been fully described in this deliverable including establishment of final architecture and integration of it to the industrial environment as well as reporting the revised KPIs related to each business scenario leveraging on RE4DY reference architecture. In section 4 the outputs of task 4.4 has been depicted introducing the POLIMI performance monitoring methodology and its two iterations and insights of the pilots on project concepts and reference architecture.

1.2 Relationships among other deliverables

This deliverable is closely related to D4.2 "Scale up & on-site validation & revised KPI assessment: Process Operations" and its related deliverables in WP2 and WP3 of the project.

2 Pilot 1: VWAE

2.1 Full-scale implementation

2.1.1 Final established architecture

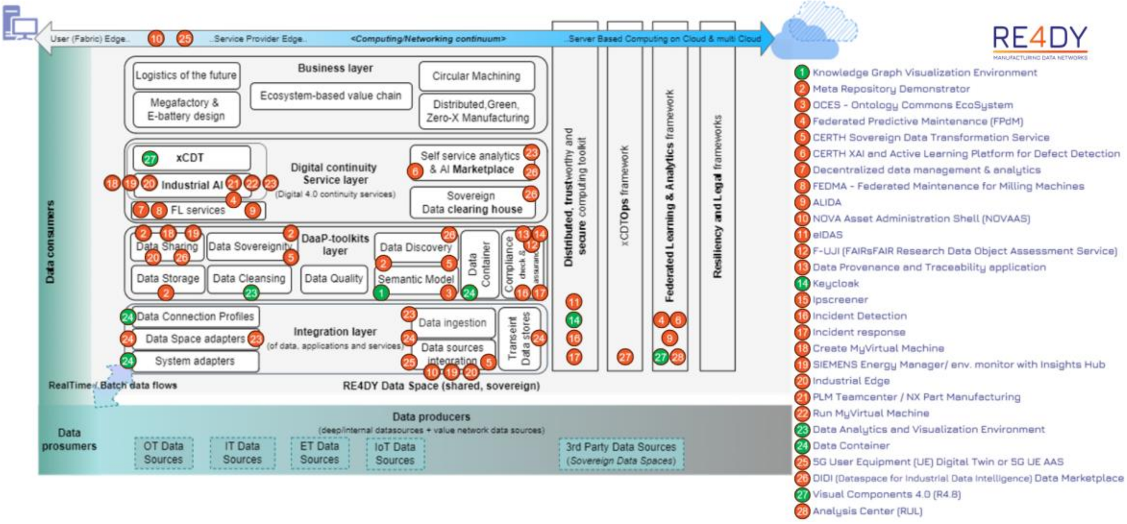


Figure 1 - Components deployed for VWAE pilot.

The final architecture of the VWAE pilot is centered around the digital twin of the logistics processes at the Palmela plant, combining planning automation, shopfloor digitization, and real-time asset monitoring. This architecture integrates simulation environments, data connectivity layers, and visualization tools to provide a unified view of logistics performance and enable resilient planning.

At the core of this setup lies the CEIT Twiserion digital twin platform, which acts as the main environment for scenario simulation and KPI-driven analysis. Twiserion enables the VWAE logistics team to design, test, and optimize material flow strategies in a realistic way, integrating data sources from GT Process, e-paper devices, and RTLS.

GT Process automation serves as the backbone of logistics planning. The system automatically executes monthly planning runs by leveraging production forecasts, logistics master data, and material flow constraints. Outputs from GT Process are configured into Twiserion, allowing planners to assess various alternatives, evaluate KPI's (lead time, workload balance), and validate decision-making against real plant conditions.

To bridge the physical and digital worlds, e-paper displays were deployed on the shop floor to replace static paper-based information. These displays are updated directly through the logistics IT systems, ensuring that newly planned GT Process configurations are instantly visible to operators. This integration not only eliminates manual updates but also ensures that the digital twin reflects real shopfloor status with minimal delay.

Another critical layer of architecture is the Real Time Location System (RTLS), implemented to monitor the movement and utilization of key logistics assets, such as tugger trains. RTLS data streams are ingested into the system and compared against Twiserion to provide real-time validation of the simulated models. This closes the loop between planned scenarios and actual shopfloor behavior, enabling early detection of inefficiencies such as idle times, underutilization, or bottlenecks.

The data integration architecture plays a pivotal role in connecting VWAE's legacy logistics IT systems with RE4DY solutions. Dedicated data connectors allow GT Process to access master data, e-paper devices to be updated seamlessly, and RTLS insights to be collected and visualized. This integration assures interoperability and paves the way for scalability firstly to other internal logistics processes and later across multiple plants in the VW Group network.

In addition, the architecture includes a reporting and monitoring layer, where KPI's from GT Process, RTLS, and shopfloor devices are combined. This provides decision-makers with a unified dashboard for logistics resilience — covering planning efficiency, asset utilization, and response time to production changes.

Overall, the pilot architecture demonstrates how simulation-driven planning, real-time monitoring, and seamless shopfloor integration can be combined into a resilient logistics ecosystem. By ensuring strong connectivity between digital twin models, IT systems, and shopfloor reality, the VWAE pilot has laid the groundwork for a scalable solution that can evolve continuously and support wider deployment across the VW Group.

2.1.2 Integration with industrial setting

The integration of the architecture into the Volkswagen Autoeuropa (VWAE) industrial environment was carried out in a straightforward manner, ensuring minimal disruption to existing processes while enabling immediate value in logistics and shopfloor operations. The implementation combines master data management, digital twin modelling, and real-time sensing technologies into a coherent workflow that supports both strategic planning and operational execution. For clarity, the impacts of integration are described across the main business processes.

GT Process and logistics optimization.

Logistics processes at VWAE rely on complex data structures sourced from multiple internal systems. The integration of the architecture has streamlined this by consolidating logistics master data into a central relational database. This data is processed through the Data Analytics Component and presented in interactive dashboards, enabling Logistics Planning Specialists to perform structured monthly scenario evaluations.

- Improved decision-making – The availability of harmonized logistics data allows planners to identify inefficiencies, compare alternative scenarios, and validate changes before implementation.
- Scenario-driven planning – The dashboards facilitate monthly what-if analyses, giving planners a clearer picture of the trade-offs between costs, efficiency, and resource allocation.

Use case: Shopfloor implementation.

On the shop floor, E-paper displays have been deployed along GT Process routes. These displays can be updated remotely with current part numbers and routing information, replacing previously manual labelling practices.

- Reduced manual effort – The digital update mechanism eliminates time-consuming manual relabeling tasks, freeing logistics staff to focus on higher-value activities.
- Increased flexibility – Rapid changes in part routing can be executed centrally and reflected immediately on the shopfloor, supporting more agile responses to production needs.

Use case: RTLS deployment for asset tracking.

Tugger trains and automated guided vehicles (AGV's) have been equipped with location sensors, feeding real-time position data into the analytics systems. This enables continuous monitoring of fleet movements across the plant.

- Enhanced utilization analysis – Real-time location data is cross-referenced with planned workflows, enabling planners to quantify asset utilization and detect under- or over-used equipment.
- Efficiency improvements – By comparing actual routing and waiting times with planned scenarios, inefficiencies are detected early, providing a data-driven basis for optimization initiatives.

Through this integration, VWAE has established a connected logistics environment where digital tools and real-time data converge to support both planning accuracy and operational efficiency. The resulting improvements (ranging from reduced manual workload to better asset utilization) directly enhance the resilience and adaptability of VWAE's logistics processes.

This integration ensures seamless interaction between software, digital twins, AI routines, and physical assets on the shop floor.

2.1.3 Key challenges and solutions for full-scale implementation

The VWAE pilot encountered several challenges during the implementation of the connected logistics solutions, ranging from data integration hurdles to change management on the shop floor. Addressing these effectively was essential to ensure successful adoption and to pave the way for sustainable full-scale deployment.

Challenge 1 – Heterogeneous logistics data sources.

A major obstacle in the early stages was the fragmentation and inconsistency of logistics master data. Information relevant to the GT Process was spread across several systems, with overlapping structures and differing levels of granularity. This made it difficult to create a reliable foundation for scenario-based analysis.

- Solution: The project consolidated the available data into a single relational database and implemented validation routines to check consistency and completeness. This harmonization not only improved data quality but also built confidence among Logistics Planning Specialists that dashboards and KPIs reflected an accurate picture of operations.

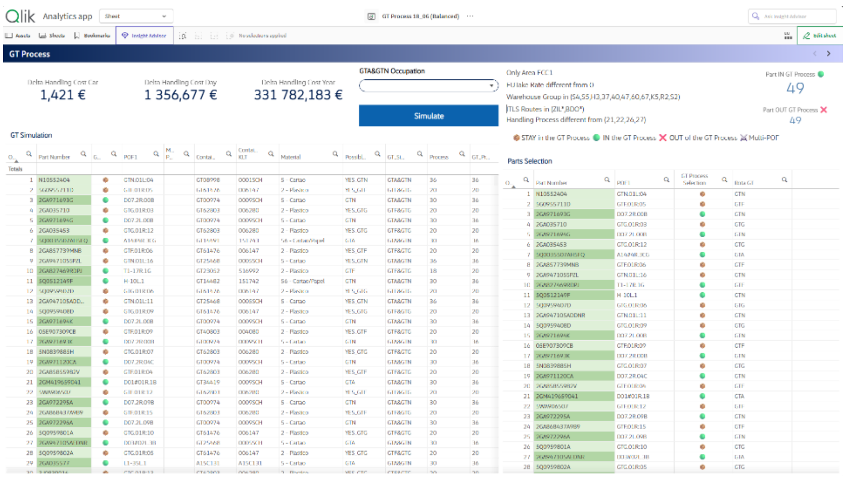


Figure 2 - Dashboard with the automatic updates of GT-Process.

Challenge 2 – Adoption of new digital tools on the shopfloor.

Introducing E-paper displays and centralized digital updates represented a clear departure from long-established manual labelling practices. It is expected that operators and logistics staff may initially express concerns, reflecting a natural resistance to new processes and technologies. However, the anticipated efficiency gains and usability improvements are expected to outweigh these initial challenges, ensuring long-term acceptance and value.

- Solution: to support smooth adoption, step-by-step guides have planned to guide future training. Early pilot planning emphasized engaging end-users in validating system functionality, ensuring that E-paper updates will align with operational requirements. This participatory approach is expected to facilitate acceptance by clearly demonstrating benefits, such as reduced manual workload and improved responsiveness to routing changes.

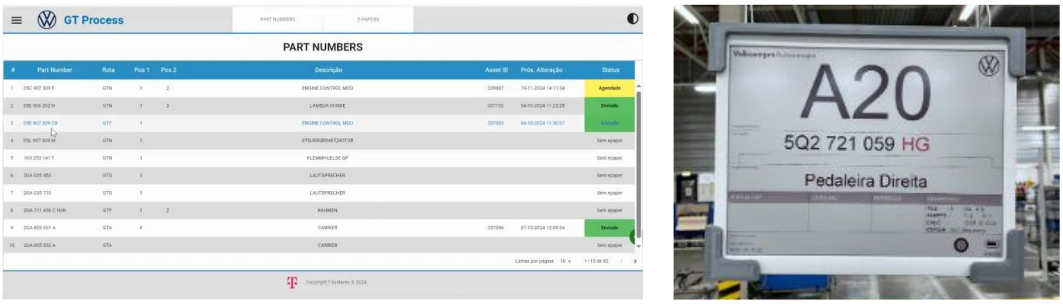


Figure 3 - E-Paper technology on the GT-Process.

Challenge 3 – Real-time location system (RTLS) accuracy and reliability.

The deployment of RTLS sensors on tugger trains and AGV's required a balance between technical precision and practical applicability. Key areas of the shop floor did not have RTLS technology deployed, making it impossible at that stage to track and trace line-feeding assets with fully reliable data across all processes.

- Solution: The planned approach focused on strategically deploying RTLS in areas where it was feasible to capture the start and end points of the majority of the processes carried out by the line-feeding assets. This targeted deployment is expected to provide sufficiently accurate data for evaluating asset utilization and comparing workflow efficiency, while keeping implementation effort and costs manageable. This pragmatic approach kept implementation cost-effective while still delivering actionable insights.

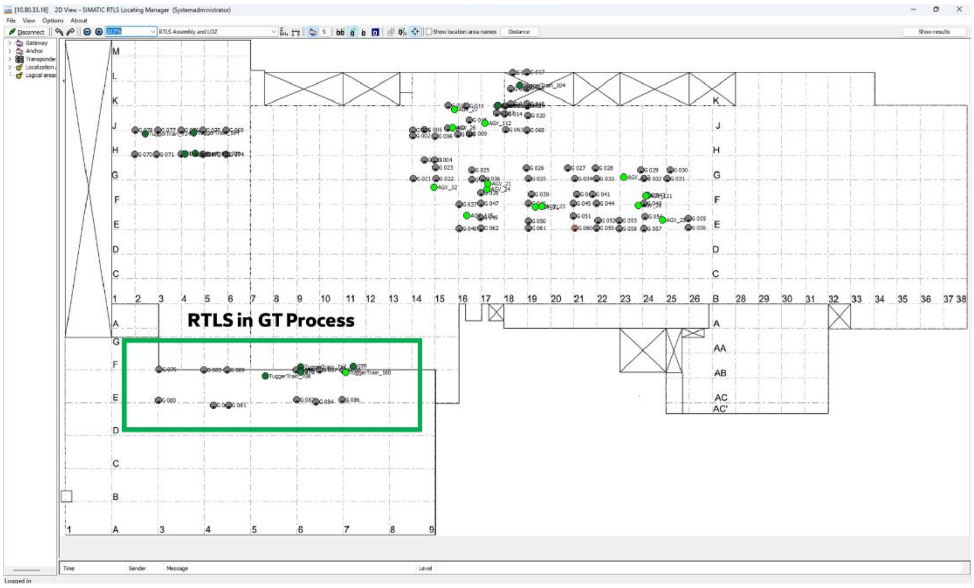


Figure 4 - RTLS Deployment in GT Process.

Challenge 4 – Change management and workflow integration.

One of the more intangible but significant challenges was embedding the new system into established VWAE workflows. Heavy changes to the update process were made in a workflow involving numerous stakeholders, requiring adjustments across multiple teams and functions.

- Solution: Concrete actions with the stakeholders were required, including extensive dissemination of the project across the different teams. A phased rollout plan was implemented to ensure full assimilation of all stakeholders without causing major disruptions. Regular meetings and iterative feedback loops reinforced the system's relevance and built acceptance gradually.

Overall, the pilot demonstrated that while technical integration can be achieved with available tools and structured data preparation, the true key to success lies in user engagement and iterative validation. By tackling resistance, ensuring data reliability, and adapting technology pragmatically to shopfloor conditions, VWAE created a realistic path toward full-scale deployment of resilient connected logistics solutions.

2.2 Industrial trials of the pilot

2.2.1 Description and objectives of implemented trials on site

The main objectives of the on-site trials were to validate the architecture and tools in real operational conditions, assess the usability of the system for shopfloor personnel and planners, and evaluate the impact on process efficiency and decision-making. Verification of the data outputs, and practical feasibility was essential to ensure that the proposed system could provide reliable support for logistics operations and scenario planning. Additionally, the trials aimed to identify potential bottlenecks or limitations in deployment to inform further improvements.

Business Process Focus: GT Process & Logistics Operations-

The trials were structured around the GT Process for line feeding and logistics management:

- GT Process Trial: Objective was to automate the monthly analysis for optimal logistics scenarios, reducing manual planning effort and associated costs. The trial focused on validating the ingestion of logistics master data from multiple sources into a Relational Database Management System, processing it through the analytics component, and generating dashboards and reports that support scenario evaluation and decision-making.
- Shopfloor Implementation Trial: Objective was to digitize GT Process updates via e-paper displays, enhancing communication, operational flexibility, and reducing manual effort. The trial tested e-paper displays along GT Process routes to allow Logistics Planning Specialists to remotely update part numbers and material flow information, assessing usability, timeliness, and correctness.
- RTLS Trial: Objective was to monitor real-time asset usage, identify inefficiencies, and simulate optimized routing scenarios. Tugger trains and AGVs were equipped with location sensors feeding data into the digital twin and analytics systems. The

trial evaluated completeness and reliability of RTLS data for monitoring asset utilization, detecting workflow inefficiencies, and supporting optimized logistics simulations.

Trial Approach:

The trials were conducted in close collaboration with logistics planners and shopfloor staff. Initial runs focused on verifying the quality and reliability of data from the dashboards and RTLS systems. E-paper updates were tested for correctness and timeliness, while dashboards were evaluated for readability and decision-making support. Iterative feedback loops allowed the project team to adjust workflows and refine analytics outputs.

Expected Outcomes:

- Automated monthly logistics scenario analysis, reducing manual effort and planning costs.
- Digitized GT Process updates, improving communication and operational flexibility.
- Real-time tracking of line feeding assets, enabling identification of inefficiencies and validation of optimized routing scenarios through simulation.
- With simulation, identify usability improvements and minor adjustments needed before broader rollout.

2.2.2 Testing procedure and activities

The testing procedures were designed to validate the system architecture, data flows, and operational tools under real-world conditions within the VWAE pilot. Trials were organized around the three main business processes: Autonomous Planning, Shopfloor Implementation, and resource Optimization. The procedures combined automated workflows, digital twin simulations, and end-user interactions to ensure both technical accuracy and practical usability.

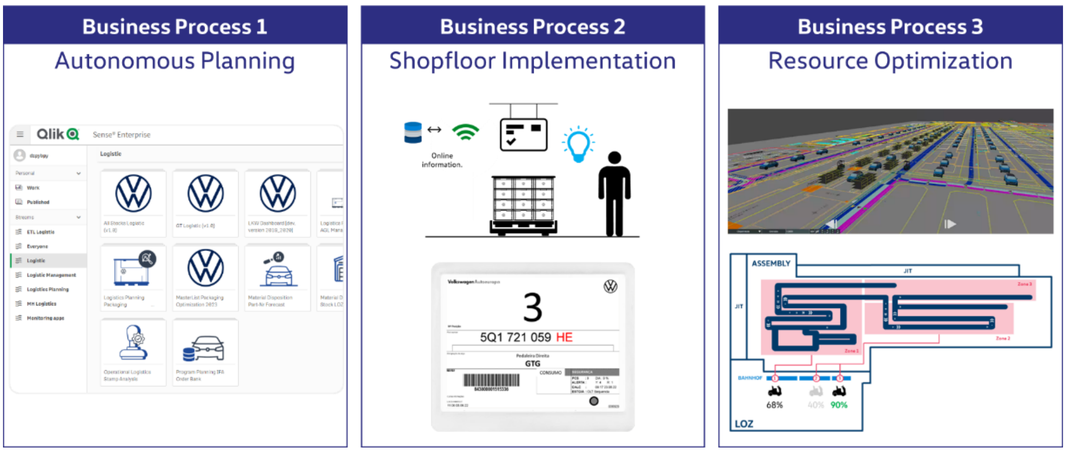


Figure 5 - Business Processes of Use Case.

Business Process 1: Autonomous Planning.

The objective of this trial was to automate monthly logistics scenario analyses, reduce manual effort, and highlight potential cost savings. The procedure followed these steps:

1. Data Integration and ETL: Logistics master data from multiple sources was extracted, missing or inconsistent values transformed, and records loaded into the database. Historical data was validated to ensure reliability.
2. Analytics and Dashboard Development: The Data Analytics Component calculated optimal GT Process configurations and generated dashboards to visualize scenario outputs and identify efficiency improvements.
3. Simulation via Digital Twin (Twiserion): Alternative logistics scenarios were simulated to compare planned versus actual operations, providing a testbed for process optimization.
4. Validation and Iteration: Logistics planners reviewed dashboard outputs and simulation results, validating recommendations, and iteratively refining scenarios to ensure actionable insights.

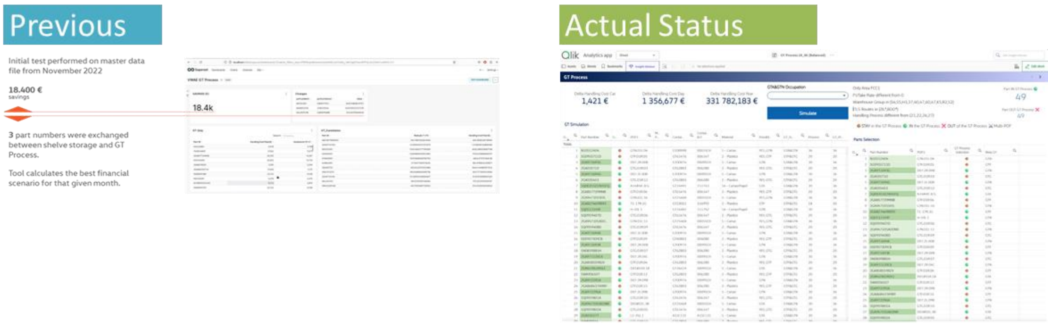


Figure 6 - Evolution of Business Process 1.

Business Process 2: Shopfloor Implementation.

The trial aimed to digitize GT Process updates via e-paper displays, improving operational flexibility and communication. Key steps included:

1. Deployment and Configuration: E-paper displays were installed at GT Process update points and configured for remote management via a web interface.
2. Workflow Verification: Shopfloor personnel tested the update process, ensuring that information appeared correctly, was timely, and reflected real operational requirements.
3. Iterative Adjustment: Feedback from operators led to refinements in display content, update frequency, and workflow alignment, improving adoption and operational efficiency.

Business Process 3: Resource Optimization.

This trial focused on real-time monitoring of line feeding assets to identify inefficiencies and simulate optimized routing scenarios. The procedure included:

1. Gateway Deployment: RTLS gateways were mounted on GT Process, focusing on areas where start and end points of processes could be reliably tracked.
2. Data Collection and Integration: X/Y coordinates were collected continuously and fed into the digital twin and analytics systems, allowing comparisons between planned routes and actual asset usage.

3. Scenario Simulation and Analysis: The Twiserion digital twin simulated alternative workflows, assessed asset utilization, and validated routing compliance. Iterative adjustments were made based on planners' insights and operational feedback.

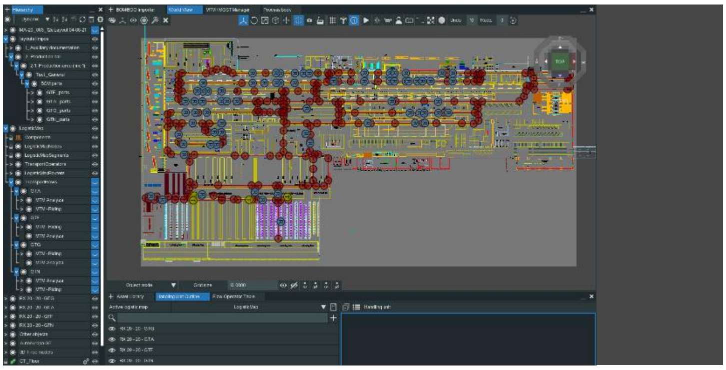


Figure 7 - Simulation of GT Process routes.

Validation Framework.

- Iterative Feedback Loops: Continuous input from logistics planners and shopfloor operators ensured tools and simulations were aligned with operational needs.
- Simulation-Based Analysis: Digital twin simulations were used to fill gaps where full RTLS coverage was not available, enabling predictive evaluation of workflow changes.
- Usability Assessment: End-users validated dashboards, e-paper updates, and RTLS reporting formats to ensure clarity, reliability, and operational relevance.

Expected Outcomes.

- Automated and accurate monthly GT Process analyses with reduced manual effort and increased scenario reliability.
- Digitized GT Process updates along the shop floor, improving communication, reducing errors, and increasing responsiveness.
- Real-time monitoring of line feeding assets, enabling identification of inefficiencies, validation of workflows, and input for optimized routing simulations.
- Identification of further improvement opportunities in user interaction and data integration workflows.

2.2.3 Barriers faced and changes with respect to the planned activities

During the execution of the testing procedures across the three business processes — Autonomous Planning, Shopfloor Implementation, and Resource Optimization — several practical, technical, and organizational barriers were encountered, requiring adjustments to the initially planned activities. These barriers stemmed from technological limitations, data availability, human adaptation, and the need to coordinate multiple stakeholders across the factory environment.

Business Process 1: Autonomous Planning.

Barrier: Data integration was challenging because, although many advancements had been made in the past to connect data silos, at headquarters level tremendous progress was achieved by integrating all data management technology into AWS. The main challenge was then to take advantage of this technology, then reliably connect the AWS mainframe to our IT infrastructure. And perform the ETL processes necessary to extract, transform, and load the required data for our use case.

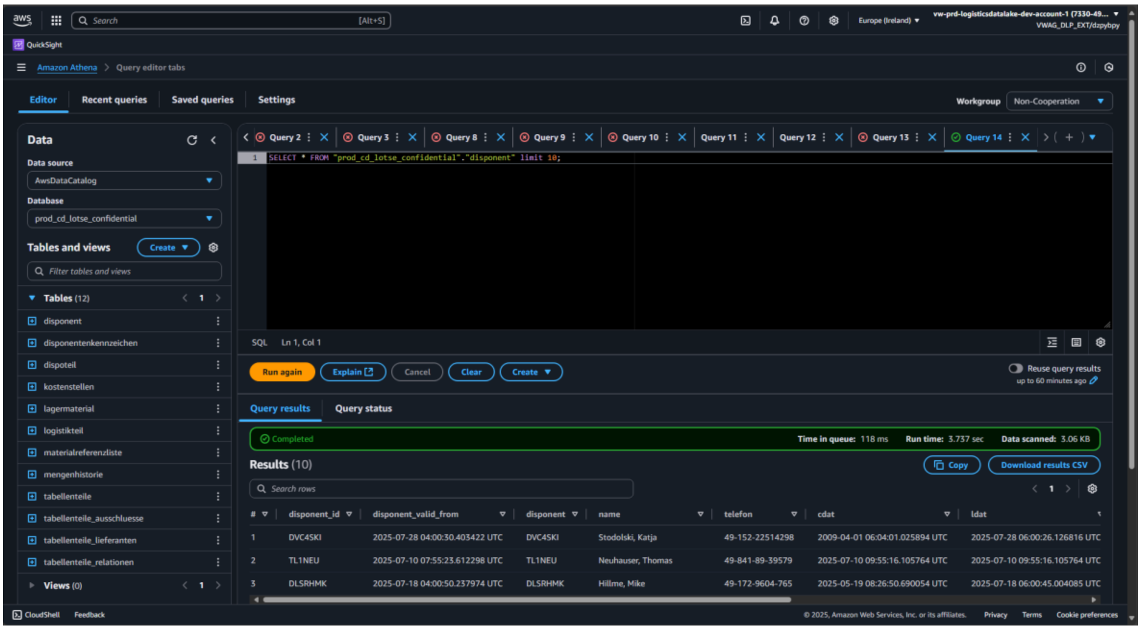


Figure 8 - AWS Logistics Data Lake.

Changes Implemented: Automated ETL workflows were deployed to harmonize inputs into the RDBMS, and validation routines were introduced to ensure historical record consistency. This allowed the GT Process dashboards to calculate reliable scenario outputs and highlight savings opportunities.

Additional Considerations: Fully leveraging the capabilities of CEIT Twiserion required training and adaptation for logistics personnel to interpret simulations and insights effectively. A period of familiarization was necessary to ensure actionable decision-making from the dashboard outputs.

Business Process 2: Shopfloor Implementation.

Barrier: The installation of e-paper displays and remote management systems required coordination across multiple teams. Significant changes to the update process involved numerous stakeholders, raising concerns over process reliability and adoption.

Changes Implemented: A phased rollout plan was implemented, combining heavy dissemination of project information across teams with hands-on training and iterative adjustments based on user feedback. This ensured total assimilation of stakeholders without disrupting ongoing operations.

Additional Considerations: Integrating pilot systems with existing cloud-based legacy data required multiple bureaucratic steps and complex IT configurations to ensure secure and reliable data flows. This integration was critical to enable seamless updates and communication between shopfloor and planning teams.

Business Process 3: Resource Optimization.

Barrier: Initial RTLS deployment coverage was incomplete, and key areas of the shopfloor lacked sufficient gateway infrastructure. Tracking line feeding assets with reliable, high-fidelity data was not possible using the initially deployed technology.

Changes Implemented: RTLS sensors were selectively deployed in areas enabling the capture of start and end points for the majority of the processes carried by line feeding assets. This pragmatic approach ensured actionable location data, enabling meaningful asset utilization analysis and workflow comparisons while remaining cost-effective.

Additional Considerations: Selecting reliable RTLS registrations for meaningful reporting required careful validation. The team filtered, interpreted, and processed raw data to extract actionable insights, supporting optimization decisions and demonstrating project value.

General Observations:

It was expected that operators and logistics staff would initially have concerns due to natural resistance to new processes. However, the benefits of automated analysis, digital updates, and real-time monitoring were clearly communicated, demonstrating that initial adaptation pains were outweighed by long-term improvements in efficiency, accuracy, and operational flexibility.

2.3 Final KPIs monitoring and validation

2.3.1 Industrial Outcomes and Lessons Learned

In general, the industrial outcomes from implementing the VWAE pilot show significant potential in enhancing logistics process planning, simulation, and operational transparency. While the system has not yet reached full deployment across the shopfloor, early trials have already demonstrated clear value in automating planning workflows, improving data integration, and enabling real-time visibility into asset usage and routing efficiency. Certain limitations remain, particularly around full shopfloor integration, learning curves, and refinement of RTLS data interpretation. Nonetheless, the results highlight a strong foundation for data-driven decision-making and process optimization.

Autonomous Planning:

The automated monthly analysis of logistics scenarios significantly reduced manual planning effort and improved scenario evaluation efficiency. By ingesting logistics master data from multiple sources into the RDBMS and processing it via the data analytics component, planners were able to quickly identify optimal GT Process configurations and highlight cost-saving opportunities. Early involvement of logistics specialists ensured that scenarios were operationally relevant and actionable.

Shopfloor Implementation:

The deployment of e-paper displays along GT Process routes allowed Logistics Planning Specialists to update part numbers and process information remotely, reducing manual interventions and enhancing operational flexibility. Initial trials confirmed that remote updates improve responsiveness and communication efficiency. Phase-by-phase rollouts and thorough dissemination across teams are critical to ensure full adoption without disruption.

Resource Optimization:

The pilot successfully monitored real-time asset usage by equipping tugger trains and AGVs with location sensors feeding data into the digital twin and analytics system. Cross-referencing RTLS data with planned workflows enabled identification of inefficient asset usage and validated simulation models for logistics optimization. Early challenges included incomplete coverage and the need to filter and validate RTLS data to extract actionable insights. The pragmatic solution involved targeted sensor deployment in key areas, capturing start and end points of the majority of line-feeding operations.

Lessons Learned:

- Dedicated Resources and Synergies: To fully unlock the potential of digital twins, synergies should be created across the entire plant. Instead of relying on a single resource to develop logistics scenarios, broader organizational commitment ensures continuous development and a stable, long-term evolution of simulation capabilities.
- Engagement of Key Stakeholders: Early involvement of IT and logistics representatives from headquarters accelerates data connectivity with cloud-based logistics systems and enables faster scalability across the group.
- RTLS Insights Definition: RTLS development should begin with clearly defined objectives. Engaging stakeholders responsible for line-feeding assets early streamlines report design, reduces rework, and ensures outputs directly support operational decisions.
- Learning Curve and Human Resources: Effective use of CEIT Twiserion required training and adaptation for logistics personnel, emphasizing interpretation of simulations and scenario outcomes.
- Legacy System Integration: Connecting AWS-hosted data to VWAE IT infrastructure required careful configuration and multiple approvals, highlighting the importance of early IT involvement.
- Pragmatic Implementation: Targeted deployment of RTLS and phased rollouts for digital tools allowed extraction of actionable insights without attempting full-scale perfection initially, keeping costs manageable while proving operational value.

Overall, linking concrete business processes (GT Process analysis, e-paper updates, RTLS tracking) to the digital twin and analytics infrastructure provided measurable efficiency improvements, validated simulation models, and built a strong foundation for further scale-up and shopfloor integration.

These lessons extend beyond the immediate pilot world and are relevant in other industrial worlds. Guidelines like building organizational synergies, engaging key stakeholders upfront, setting goals for technology tracking, and adopting practical phased deployments can be followed by other organizations when implementing digital twins, real-time monitoring, and data-driven process improvement. By replicating these learnings, industries can accelerate adoption, reduce risk, and derive maximum operational benefit from digital technologies.

2.3.2 KPI Measurement and Performance Evaluation

The KPI's for the VWAE pilot focus on evaluating the impact of the GT Process digitalization, e-paper implementation, and RTLS deployment / simulation on logistics performance, process flexibility, and knowledge management. These indicators measure improvements in cost efficiency, planning agility, implementation speed, and digitalization of operational knowledge, and are categorized according to business process objectives.

KPI Measurement Approach.

- Operating Cost Reduction: Evaluated by comparing GT Process logistics costs before and after the automated monthly analysis. Reductions are quantified through measurable savings with logistics service providers.
- Changeover Planning Time: Measured by the average time required to define and finalize optimal GT Process configurations using automated workflows, demonstrating improvements in process flexibility and responsiveness.
- Iteration and Implementation Time: Evaluated using RTLS data to calculate the percentage of time line-feeding assets spend within expected operational zones, reflecting faster deployment and reduced manual intervention.
- Digitalization Capabilities: Assessed by the successful deployment of E-paper displays and the use of dashboards to monitor start/finish times of the GT Process, providing actionable insights for decision-making and process transparency.

ID	BUSINESS Indicators	DESCRIPTION	Unit	Initial value	Expected final Value	Expected Date of achievement
1	Operating cost reduction: logistics cost for the GT Process	Automated monthly analysis anticipates cost reduction versus traditional quarterly or semesterly manual analysis. Optimal processes reduce effort and costs for the logistics service provider and decrease overall product cost.	€	Confidential	5% increase in savings with GT Process	Before 6 months after implementatio n
2	Changeover planning time shortening	Increased process flexibility by reducing the average time spent designing optimal scenario configurations for the GT Process. Faster scenario updates enhance adaptability and	Average time in planning phase	≥5 working days with effort from logistics service provider	-10%	Before 6 months after implementatio n

		responsiveness. Simulation of different GT Process configurations further increases system flexibility.				
3	Decrease of iteration and implementation time	Less time designing optimal GT Process solutions. Quick and autonomous upload of GT Process master data and remote updates of E-Papers accelerate deployment. Digital twin utilization reduces asset occupation time for routes GTA, GTG, and GTF.	Average time on implementation	≥8 working days with substantial effort from logistics service provider	-10%	Before 6 months after implementation
4	Digitalization: improved knowledge on process performance	Digital workplace provides actionable insights for optimization with shortened lead times. Key strategic information is displayed through e-paper dashboards, enabling a paperless process and enhanced process transparency.	Digitalization capabilities	No control of start/finish GT Process. No E-Papers	Dashboard to control start/finish GT Process. E-Papers installed on GT Process	Before 6 months after implementation

KPIs measure different aspects of a business, gaining and improving logistics processes. To illustrate, lower operating cost fosters a more cost-efficient collaboration with logistics service providers, which culminates in lower total product cost. Also, shorter planning times for changeover directly improve reconfiguration route responsiveness and adaptation to production shifts. Digitalised dashboards and e-paper displays foster real-time knowledge dissemination which enhances process transparency and improves knowledge-driven decisions. Together, these impacts help explain how each KPI impacts a given business process and emphasize the operational relevance in Figure 9.

ID	Indicator	Description	Current Value	Future Value	BP1	BP2	BP3
1.	Operating **cost reduction:** logistics cost for the GT Process	Automated monthly analysis anticipates opportunity for cost reduction of logistics service versus semesterly or quarterly manual analysis.	Confidential.	**5%** reduction	✓		
2.	Changeover **planning time** shortening	Increase in process flexibility with the reduction of the average time spent conceiving the optimal scenario configuration for the GT Process.	> 5 Working Days with some effort from service provider.	**10%** reduction	✓	✓	✓
3.	Decrease of **iteration** and **implementation time.**	Quick and autonomous upload to digest GT Process master data decreases implementation times, especially on laborious tasks carried out by logistics planners.	> 8 Working Days with significant effort from service provider.	**10%** reduction	✓	✓	✓
4.	**Digitalization**: improved knowledge on the process performance.	Digital workplace with insights to assess and execute optimization with shortened lead times. Paperless process.	No control start/finish of GT Process routes. No E-Papers	Dashboard to control start/finish GT Process. E-Papers on GT Process.		✓	✓

Figure 9 - Relationship between business indicators and business processes.

Summary:

The KPI's confirm that the VWAE pilot delivers tangible benefits in cost efficiency, planning agility, implementation speed, and digitalization of GT Process operations. Linking each KPI to a specific business process and measurement method allows for precise evaluation of the pilot's effectiveness and guides further process optimization.

2.3.3 Final KPI Assessment and Business Impact

ID	BUSINESS Indicators	DESCRIPTION	Unit	Initial value	Expected final Value	Expected Date of achievement	Current KPI Assessment
1	Operating cost reduction: logistics cost for the GT Process	Automated monthly analysis anticipates cost reduction versus traditional quarterly or semesterly manual analysis. Optimal processes reduce effort and costs for the logistics service provider and decrease overall product cost.	€	Confidential	5% increase in savings with GT Process	Before 6 months after implementation	19% reduction due to contract adjustment with logistics service provider: big adjustment in parts on GT Process. 5% saving possible for October 2025 onwards but needs validation because of contract adjustment.
2	Changeover planning time shortening	Increased process flexibility by reducing the average time spent designing optimal scenario configurations for the GT Process. Faster scenario updates enhance adaptability and responsiveness. Simulation of different GT Process configurations further increases system flexibility.	Average time in planning phase	≥5 working days with effort from logistics service provider	-10%	Before 6 months after implementation	Best scenario 40% reduction. Most likely scenario 20% reduction: ≤4 working days.
3	Decrease of iteration and implementation time	Less time designing optimal GT Process solutions. Quick and autonomous upload of GT Process master data and remote updates of E-Papers accelerate deployment. Digital twin utilization reduces asset occupation time for routes GTA, GTG, and GTF.	Average time on implementation	≥8 working days with substantial effort from logistics service provider	-10%	Before 6 months after implementation	Best scenario 50% reduction. Most likely scenario 40% reduction: ≤5 working days.
4	Digitalization: improved knowledge on process performance	Digital workplace provides actionable insights for optimization with shortened lead times. Key strategic information is displayed through e-paper dashboards, enabling a paperless process and enhanced process transparency.	Digitalization capabilities	No control of start/finish GT Process. No E-Papers	Dashboard to control start/finish GT Process. E-Papers installed on GT Process	Before 6 months after implementation	Dashboard available. E-Papers installed. Potential for optimization of approx. 6%

The implementation of the digital twin software architecture for the VWAE GT Process pilot has introduced a new level of transparency, efficiency, and flexibility to logistics planning and shopfloor operations. While the KPI's in this section primarily focus on time savings, cost reduction, and process digitalization, the overall impact extends to improved operational decision-making, enhanced knowledge of process performance, and strengthened organizational capabilities. The pilot demonstrates the tangible benefits of combining automated GT Process analysis, E-paper deployment, RTLS-based monitoring and simulation on a digital twin.

Operating Cost Reduction – Logistics Cost for the GT Process

The automated monthly analysis enabled by the digital twin has reduced reliance on labor-intensive, periodic manual scenario evaluations. By optimizing GT Process workflows, internal logistics effort is minimized, leading to cost savings with logistics service providers. Initial evaluations suggest that, compared with previous semi-annual or quarterly manual assessments, cost reductions of approximately 5% are achievable within six months after implementation. This demonstrates measurable cost savings and better resource allocation.

In addition to these recurring improvements, the data analytics team carried out a detailed examination of the GT Process from the logistics service provider contract, uncovering structural inefficiencies and hidden opportunities within the existing process configuration. This in-depth analysis enabled the team to propose fundamental redesigns of the GT Process setup, unlocking significant savings beyond the routine optimization cycle.

For example, the autonomous process algorithms were adapted to account for a wider set of variables, including not only high-demand part flows but also container types (such as carton packaging, which carries distinct financial implications), rack arrangements, and quantity optimization. By combining contract insights with digital twin simulations, the team was able to reconfigure the logistics setup to align with ideal package structures, ensuring both lower service costs and more efficient shopfloor operations.

The impact of these early interventions was immediate and substantial. Even before the monthly update process was fully operational, the redesigned GT Process yielded savings on the order of several hundred thousand euros, highlighting the strategic value of deep process analysis combined with digital twin-based scenario testing. Given the scale of these savings, this outcome represents a critical success factor of the pilot and demonstrates that digitalization can deliver transformational impact when coupled with organizational commitment and cross-functional expertise.

Changeover Planning Time Shortening

Automated workflows and scenario simulations allow faster configuration of GT Process setups. Prior to the pilot, logistics planners typically spent 5 or more working days coordinating and defining optimal scenarios for each monthly update. With the digital twin-enabled system, the time required to finalize configurations decreased by roughly 10%, significantly improving responsiveness and flexibility of the logistics system. This reflects efficiency gains through reduced planning effort and faster scenario updates.

Decrease in Iteration and Implementation Time

Remote updates of E-paper displays and rapid integration of master data into the digital twin reduced implementation delays. Previously, implementing GT Process adjustments required 8 or more working days with substantial planner effort. By enabling faster upload, real-time validation, and immediate deployment to shopfloor devices, iteration and implementation times decreased by around 10%, supporting more agile operations and reducing asset occupation time for routes GTA, GTG, and GTF. These improvements contribute to operational flexibility, enabling faster adaptation to changes.

Digitalization – Improved Knowledge on Process Performance

The pilot enabled a digital workplace with dashboards and E-paper displays, providing end-to-end visibility of GT Process start and finish times. Before implementation, no centralized monitoring or process insights existed. After deployment, planners and logistics personnel could assess workflow performance, identify bottlenecks, and monitor compliance in real time. This paperless system improves decision-making, reduces human errors, and enhances knowledge sharing across teams. It also strengthened organizational impact, equipping logistics teams with predictive insights and enabling more strategic decision-making and improved internal collaboration.

Lessons Learned and Observations

- Dedicated Resources and Synergies: To fully leverage the digital twin, organizational commitment across all involved teams is critical. The pilot highlighted the importance of coordinated efforts between logistics, IT, and shopfloor teams for continuous development and long-term evolution of simulation capabilities.
- Stakeholder Engagement: Early involvement of key logistics representatives and IT staff was essential for smooth integration with AWS cloud infrastructure, ensuring reliable data flows and scalable connectivity.
- RTLS Insights and simulation on digital twin: Defining meaningful metrics for line-feeding asset utilization was crucial. The pilot demonstrated that careful selection, validation, and interpretation of RTLS data directly informed process optimization decisions and enhanced KPI measurement reliability.
- Incremental Implementation: Phased rollout of E-paper displays and RTLS sensors enabled targeted validation and minimized disruption, allowing the team to demonstrate early value before full shopfloor deployment.

Key Business Outcomes

- Cost Savings: Optimized GT Process led to a measurable reduction in internal logistics costs and better resource allocation.
- Efficiency Gains: Remote updates and autonomous planning reduced planning and implementation times.
- Operational Flexibility: Real-time monitoring and simulation increased system responsiveness and adaptability.
- Organizational Impact: Logistics teams benefited from digital tools and predictive insights, enabling more strategic decision-making and improved internal collaboration.

Overall, the KPI assessment demonstrates that VWAE's GT Process pilot has achieved measurable improvements in logistics cost efficiency, planning agility, and process digitalization. The integration of digital twin technologies provides clear value in transparency, efficiency, flexibility, and organizational learning, positioning the architecture to become a key enabler of efficient and resilient logistics processes with full shopfloor deployment.

3 Pilot 2: AVL-FILL

3.1 Full-scale implementation

The pilot "Electric Battery Product/Production System Engineering" by AVL, FILL and VIS is set up to accelerate product design workflows, optimize production and to build up resilient manufacturing networks. It is focusing on the manufacturing ecosystem e-mobility, as described in previous deliverables and is driven by AVL. AVL is providing prototype manufacturing and process development for their customers as well as performing production and plant planning for the series production of the OEMs. FILL is supporting the production planning process as an expert for customized turnkey solutions for automation. VIS is supporting with the software solution on simulation. Both are tech providers.

3.1.1 Final established architecture and components

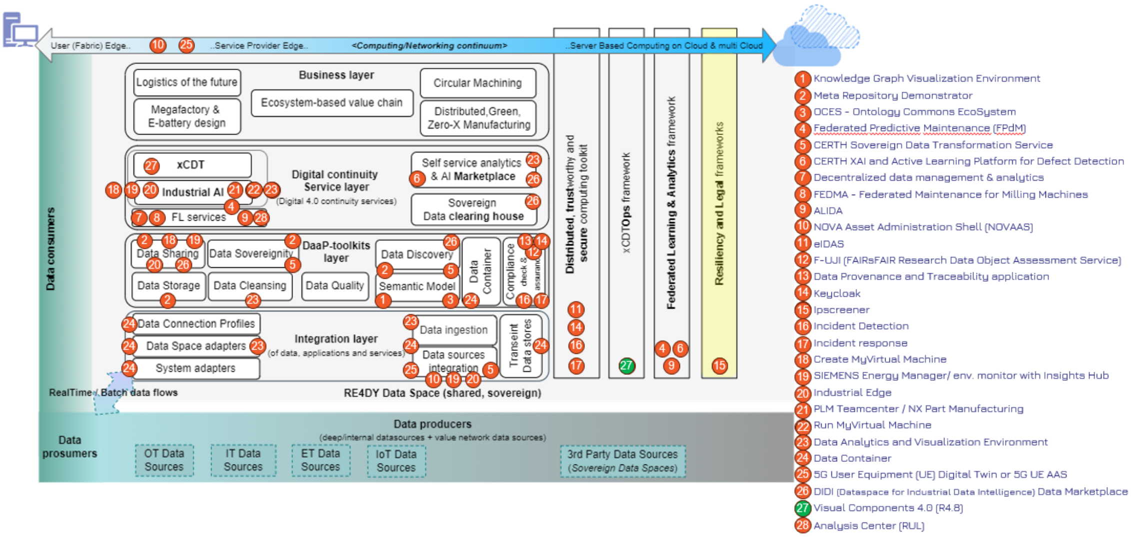


Figure 10 RE4DY Toolkit overview

The final architecture of the pilot is entirely built around the digital twin of AVLs' Battery Innovation Center. The Visual Components software provides the environment for this digital twin and therefore, is the main access point for a user of this architecture. The software itself enables AVL to simulate production processes realistically and offers insights into tact times and resource utilization. With the aim of resilient production processes, the Visual Components' functionalities have been extended with various plugins.

Starting with the CAD data management system which had been developed in order to fasten up the simulation setup process to match the requirements of agile production planning. Using the 3DXML file format for exchange between the CAD program specifically CATIA V5 and Visual Components. Not only to enable an automated simulation setup process, but also to enrich the CAD data with metadata, the battery design is exported from CATIA using an add-on. To get the key information about how the battery should be produced within AVLs' BIC (Battery Innovation Center) the digital twin can be looked at as four production cells. The user of the CATIA add-on can indicate the order of which the product passes these production cells, and which components of the product are being processed within them. The user has complete freedom to choose if and how often a production cell can be passed. Information about the components material and inertia matrices are gathered automatically. The 3DXML file can afterwards be imported using the Visual Components plugin, that reads the extension and uses its information to create the correct material flow through the digital twin. Also, as the 3DXML file contains a position matrix for each of the battery's components, the plugin can use this data to create programs for cell stacking, welding and gluing. A key advantage of this approach is, that although 3DXML files are freely expandable, the basic file stays readable for other applications. Furthermore, as the production planning process is outsourced to a production specialists like FILL, there is only one low volume file that needs to be shared.

In addition, the batteries metadata are also used in what has been called resiliency check. This check was created to get a quick answer on if the battery in question can be manufactured within the factory by used of existing machinery and tools. This check is based on data like components dimensions to compare with tool capacities and materials to take a look at chemical resistances and weldability. Therefore, this application requires up to date testing data and accurate metadata.

In order to have a digital twin that stays close to the real factory the plugin also connects the BICs SQL-server to the simulation. Its data is being used to display production errors in the simulation. This method is especially helpful, as these errors are normally very difficult to predict. They occur irregularly, may vary over time e.g. because of machine wear and strongly depend on product. Therefore, the production of prototype batteries and in particular batteries with prototype cells profits most from this approach. Furthermore, the data from the SQL-server can also be used to validate simulations.

Another application developed for this pilot is the robotic energy optimization plugin. It can be connected to robots of the digital twin, to use its kinematics especially its joints accelerations to calculate the necessary torque and therefore the energy consumed. This allows to predict the energy consume for the production of new batteries and is a basis for optimising robot programs in terms of energy consumption, e.g. by reducing vertical movements or coordinating two robots to reduce spikes.

For a more comprehensive look on the productivity a human resource simulation has been introduced. In prototype production like most of the BICs work, manual labour accounts for a large part of the work, making a better planning opportunity very valuable for AVL. With this simulation each operator in the digital twin gets a skills level which is evolving over time and also can be assign with abilities like being able to drive a forklift.

Out of the necessity of storing and processing data within the digital twin the data node has been developed. These data nodes can be connected to components like robots or to humans. When connected to components the nodes can be used to track the consumption of electric energy as well consumption of compressed air and out of it calculate the CO_2 emissions and production costs. When interacting with humans the nodes are used to manage the human resource simulation and also calculates personal costs.

The last tool used in this pilot integrates the digital model of 5G networks with the digital model of industrial plants, created by UMH (Universidad Miguel Hernandez de Elche). Specifically, it merges industrial digital models created in Visual Components with a 5G digital model, implemented as an Asset Administration Shell (AAS) of a 5G system (the AAS of the 5G system has been developed in the framework of WP3 of the Re4dy project). These two models are interconnected using an OPC UA-based interface. Our objective is to utilize this tool to assess the benefits and impact of employing 5G communications within the pilot scenario. Before proceeding with the study in the pilot scenario, the potential of the integrated tool was assessed using a sample industrial production plant. These initial tests aimed to demonstrate the tool's capability to analyze the impact of 5G communication performance on the operation and productivity of industrial processes.

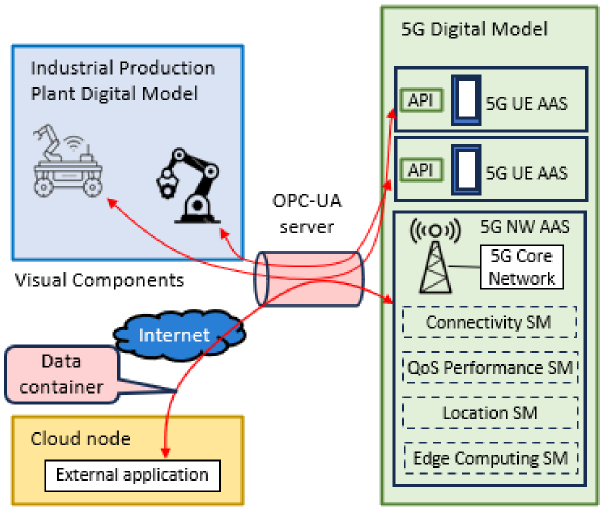


Figure 11 Architecture for integrating 5G and industrial digital models

This evaluation seeks to demonstrate the importance and necessity of integrating 5G into industrial digital models for their joint design and optimization. The 5G digital model includes an AAS of the 5G UE (User Equipment) and an AAS of the 5G NW (5G Network). The 5G AAS is presented and described with details in WP3 deliverables. The UE serves as the termination point of a 5G link, and the NW models the most relevant functions of the 5G Radio and Core networks. The 5G UE and NW AASs have been implemented following 5G-ACIA guidelines and Platform Industrie 4.0 specifications. Both AASs follow a functional design where information is structured and grouped by functions or operations rather than by physical nodes, making the model scalable and easy to extend or modify. The information provided by an AAS is organized in digital sub models, and the data contained in the sub models are referred to as sub model elements.

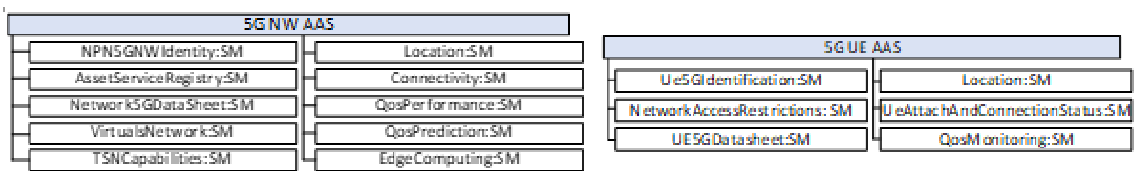


Figure 12 5G digital model AAS

3.1.2 Integration with industrial setting

The integration of the software architecture with the industrial setting is held very uncomplicated. FILL as well as AVL use Visual Components enriched with the plugins mentioned before to run the BICs' digital twin. Both companies work within different use cases and therefore use different components of the architecture. For a better illustration of the use of these components as well as their impacts on the companies' workflows. Further explanation will be split up into these use cases.

Use case 1: battery design

Every design process of any technological product is defined by making decisions and compromises depending on the target outcome, available data and experience. Thereby, many different influencing factors have to be considered ranging from technical specifications like weight, power or especially in e-mobility energy density, over production related limitations to economic requirements. A designer has to have all of these factors in mind during the whole design process. In order to take some load of, the digital twin approach should support the employees on making decisions and therefore make the whole process faster, with even better product quality.

Enhanced product quality – By utilising the BICs' digital twin and the automated simulation setup tool in combination with the CATIA add-on for enriched 3DXML export, the production of a product in development can be visualised with almost no effort. This may lead to a deepened understanding of the different production processes within the BIC and therefore enhances the decision-making background of the designer. Additionally, the resiliency check can be used to point out possible trouble spots of the design in terms of production.

Faster design process – The previously mentioned tools also influence the workflow of designers in a second way. Product design by nature involves iterative loops, as it is rarely possible to foresee all potential issues in advance due to the complexity of modern systems. While these iterations are essential for refining the design, they are also time-consuming. These iteration loops can be shortened by integrating the simulation into the designers' workflow. This leads to a more efficient design process, enabling faster and more cost-effective development.

Use case 2: process planning and optimisation

Production process planning is the strategic task of designing and organising manufacturing workflows to ensure efficient, timely and cost-effective production. It involves coordinating resources, machines, and labour while aligning with product specifications and delivery targets. However, planners often face difficulties in making precise decisions due to the complexity and the variability of production environment. Uncertainties such as equipment performance, material availability and human factors make it difficult to predict outcomes accurately.

The integration of BICs' digital twin architecture into the process planning workflow significantly transforms how planners approach production design, validation and optimisation. By embedding simulation, automation and real-time data into a unified environment, the software architecture delivers measurable improvements across several key areas of the planners' daily operations.

Enhanced accuracy - By simulating the entire production process within Visual Components – including cell routing, robot operations and human tasks – the planner gains a highly realistic view of how the factory will operate. This leads to more precise planning outcomes and reduces the risk of errors afterwards.

Increased planning efficiency - The automated simulation setup using extended 3DXML files drastically reduces the time required to prepare production scenarios. Process planners no longer need to manually configure material flows and robot programs from scratch, allowing them to focus on detailed planning and strategic decisions rather than repetitive tasks.

Data-driven decision making – The connection to the BICs' SQL server enables planners to incorporate real production data, including error patterns and machine performance, directly into their simulations. This allows for predictive adjustments and validation of planning assumptions.

Energy consumption and emissions – With the robotic energy optimisation plugin, planners can simulate and analyse energy consumption based on robot kinematics, instead of having to extrapolate from recorded data. Also, the implemented CO_2 emission calculation eliminate the need for manually calculating. The need for knowing the CO_2 emissions of the product gains importance as it is needed for the upcoming battery passport and therefore can be a selling proposition.

Use case 3: mobile robots

The last use case focuses on AGVs and their guidance using 5G networks (NW). It contains the following three scenarios:

- *Scenario 1.A - Distributed control:* In this case, each AGV runs its own guidance control application locally on its onboard control unit. In this scenario, AGVs periodically exchange their positions over the 5G network to avoid potential collisions among them.
- *Scenario 1.B - Centralized control:* In this second case, the guidance control application is implemented in a computing node external to the AGVs for a centralized control of the AGVs, which also allows to reduce the computing capabilities of the AGVs, also reducing cost.
- *Scenario 2 - Collision avoidance:* The position of the 5G-enabled device is continuously updated in the 5G UE AAS, and the AAS facilitates access to this data through the implemented OPC UA interface. In this case, the Collision avoidance application (that can be implemented in the Cloud or in an edge node) subscribes to periodically received information about the position of all AGVs in the scenario in the 5G AAS.

3.1.3 Key challenges and solutions for full-scale implementation

One of the first hurdles is the steep learning curve associated with the new tools. The architecture involves multiple components such as Visual Components and its custom add-ons. These require a solid understanding of both the software and the underlying production processes. Therefore, adapting to the digital twin environment can be overwhelming at first and cause resistance to changing the employee's workflow, especially if the new system initially appears more complex or less intuitive. This can slow down adoption and reduce effectiveness in early stages.

In order to counteract to this humane behavior, several employees underwent trainings provided by Visual Components for their software. The understanding of the programs' structure gained by these training courses helps a lot in terms of acceptance and provided the basis for understanding every further development of the pilot. Concerning the plugins, videos for explaining the functionality were made, but further explanation was provided directly from the developers of the software. This approach was especially helpful during development as it allows direct feedback from the users.

Another key challenge encountered during the simulation was the quality of the available data. In particular, factory-sourced data was often incomplete or inconsistent, leading to a need for thorough data preparation. To avoid the timely expense and complexity of integrating a new data preparation system, the pilot project leveraged existing tools already in use at AVL for data analysis. This approach allowed the team to concentrate on the pilots' core objectives without diverting resources to tool integration. Moreover, by utilizing the same data sources and tools as other AVL applications, the project ensures consistency company wide and facilitates easier data oversight and maintenance.

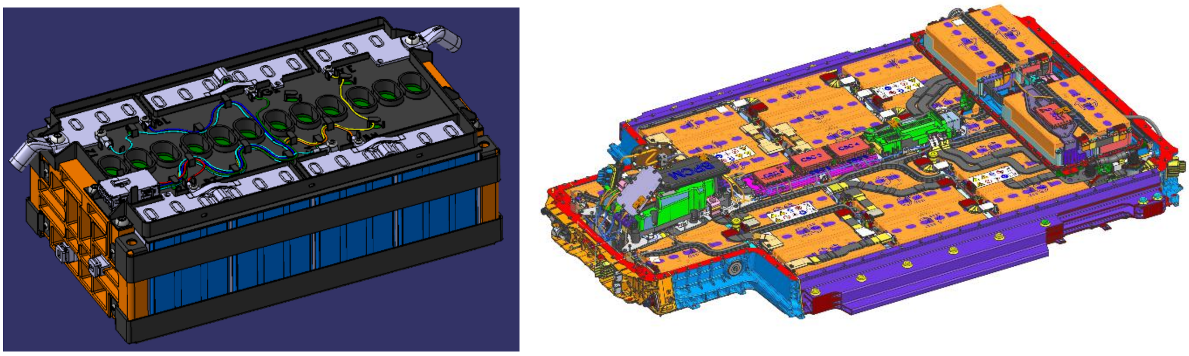


Figure 13 Range of complexity of AVL designs

A foreseeable but still not trivial challenge was caused by the complexity and variability of the battery designs. Developing a structure for metadata that fits all batteries and still has valuable, consistent information in it, was more challenging than expected. This results from the broad range of products AVL designs and produces within the BIC. Therefore, the metadata structure must be capable of describing everything from a little module to a whole battery pack, as well as products based on every cell type. After many different approaches to this problem the only option left was trial and error. As a result, the software was tested with several different battery designs, trying to capture every possible distinctiveness. Nevertheless, a compromise had to be made between the amount of information to be shared - and therefore the level of detail, both of the description of the battery and the results of the resiliency check – and the flexibility of the software in terms of battery design.

3.2 Industrial trials of the pilot

3.2.1 Description and objectives of implemented trials on site

Generally, the trials' objectives were the verification of the simulation results, as well as gaining insight into the benefits and drawbacks of the new workflows. The verification process is especially important as the user needs to be able to rely on those outcomes or at least needs to know what kind of insecurities are still to be expected. Otherwise, the software will not be able to compete with traditional methods. So as the verification of the results are providing the basic information of effectiveness, the investigation on the impacts on the workflow may provide information about the efficiency and points out possibilities for further improvement. The trials were conducted within the context of the separate use cases as also described in 3.1.2.

Use case 1: battery design

In the design use case, the focus was on testing the usability of the different tools. Therefore, these trials results relied heavily on the designer's subjective perceptions. The accuracy of the results was not that important as the designer does not need to make any detailed decisions concerning production. Also, verification of the simulation results was difficult, since the battery designs were still in development during this phase and therefore had no physical representation. Trials using data from existing batteries were not conducted, since the tools could be tested again in the second use case.

Use case 2: process planning and optimisation

The trials in this use case were conducted collaboratively by production planning specialists from both AVL and FILL, with a focus on validation of simulation results and the practicality of the digital twin-based tools. Using existing CAD models and production data, the teams tested the full software architecture. Whereas the results of some tools like energy consumption and cycle time analysis could be directly compared to measured production data, the whole CAD data management system can only be evaluated based on the amount of work, that it can save. Most difficult to assess is the human resource plugin. Due to its nature as a long-term analysis the simulation needs to be observed and adjusted for a longer period of time.

Use case 3: mobile robots

To demonstrate the benefits of using an integrated digital model of 5G networks and industrial plants, the Mobile Robots use case was selected focusing on two representative applications: guidance control and collision avoidance. The use case considers AGVs that transport material from a warehouse to production lines.

- *Scenario 1.A - Distributed control:* As presented before, each AGV runs its own guidance control application locally on its onboard control unit. In this scenario, AGVs periodically exchange their positions over the 5G network to avoid potential collisions among them. When an AGV does not receive the position of the other AGV for a specified period of time (referred to as survival time or t_{SUR}), the AGV stops for safety reasons. The AGV will resume its movement after receiving the messages from the other AGV at the expected rate during a period t_{res}. Figure 14 depicts the exchange of messages between the various components in the integrated 5G and industrial digital models. When AGV1 wants to send its position to AGV2, it sends a message to the 5G UE1 deployed on the AGV1. The 5G UE1 then informs the 5G NW that it has a new message to transmit. The 5G NW uses the *QosPerformance* sub model to model the 5G link performance and determine if the message transmissions from UE1 to the gNB and from the gNB to UE2 are satisfactory. The 5G NW notifies the 5G UE1 and UE2 whether the message has been transmitted with or without error. If the message is successfully transmitted on both links (UE1-gNB and gNB-UE2), UE2 notifies the AGV2 of the new position update received from AGV1.

In this scenario, we consider that the latency experienced in the transmission of the messages from AGV to the other is negligible (since the packet is routed from the AGV1 through the 5G network to the AGV2). As a result, a packet cannot be received correctly due to propagation errors and then it is discarded. If the packet is correctly received, the latency experienced is null.

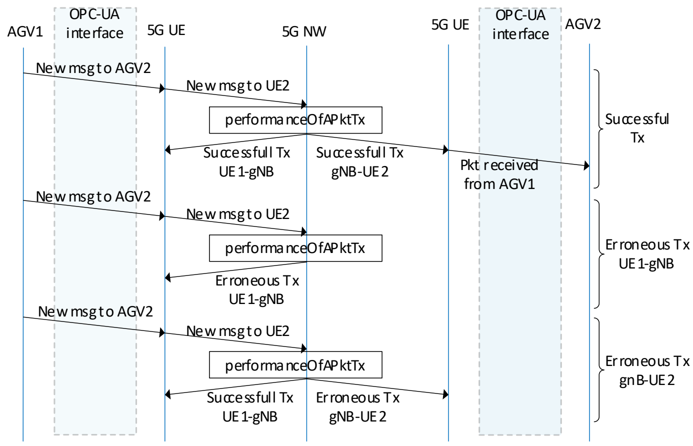


Figure 14 Message exchange between different entities of the integrated 5G and industrial digital models

- *Scenario 1.B - Centralized control:* In this second case, the guidance control application is implemented in a computing node external to the AGVs for a centralized control of the AGVs, which also allows to reduce the computing capabilities of the AGVs, also reducing cost.

  In this case, AGV1 and AGV2 subscribe to the guidance control application. The AGVs periodically send information about their current position to the guidance control application through the 5G network. The guidance control application continuously calculates the optimal path for both AGVs and transmits driving commands periodically through the 5G network to the AGVs to ensure safe and coordinated movement. When the time spent from the reception of the last driving command by an AGV is higher than a survival time or t_{sur}, the AGV stops for safety reasons. The AGV will resume its movement after receiving driving commands from the guidance control application at the expected rate during a period t_{res}.

The interaction between the various components in the integrated 5G and industrial digital models and how the latency experienced in the packet transmission is calculated is different whether the guidance control application is located in an edge computing node or in the Cloud as shown in Figure 16 and Figure 16 (for simplicity, figures only show an AGV but multiple AGVs interact in the scenario in the same way as shown in the figures for AGV1). When the Guidance control application is located in the Cloud (Figure 13), the *PerformanceOfAPktTx* operation in the *QosPerformance* sub model of the 5G NW AAS estimates the latency $L_{UE\text{-}gNB}$ experienced in the transmission of the position data from the AGV to the 5G gNB, and the latency $L_{gNB\text{-}UE}$ experienced in the transmission of the command sent by the Guidance control application to the AGV between the 5G gNB and the AGV. The 5G NW AAS sends data via the Internet to the Guidance control application, and the Guidance control application sends commands to the 5G NW through Internet. We measure the real latency experienced by the data/command when it is transmitted between the 5G gNB and the remote application – $L_{gNB\text{-}App}$ and $L_{App\text{-}gNB}$ –, and the processing time in the Guidance control application -L_{App}-. When the Guidance control application is located in an edge cloud near the gNB, the data/commands exchanged between the AGVs and the application do not travel through the Internet, and the latency experienced is lower. As shown in Figure 14, the latency experienced in the transmission of the data/commands between the 5G gNB and the Guidance control application – $L_{gNB\text{-}App}$ and $L_{App\text{-}gNB}$ - is also estimated by the *PerformanceOfAPktTx* operation in the *QosPerformance* sub model considering that the application is located in an edge computing node close to the gNB. Moreover, the processing time needed by the Guidance control application is also estimated by the *AppProcessingTime* operation of the *Edge Computing* sub model of the 5G NW AAS considering the computing capability of the edge node.

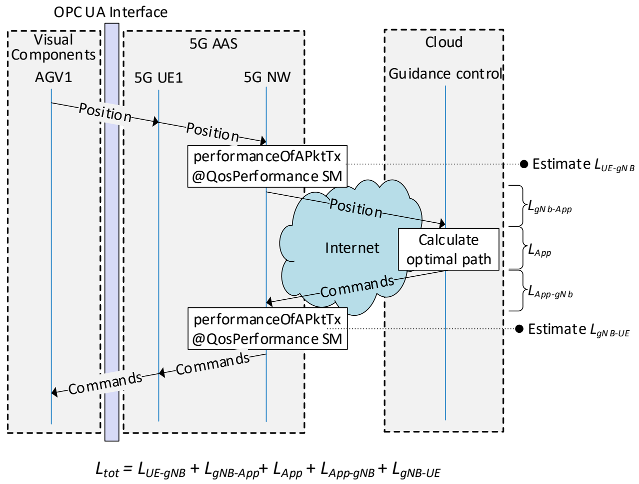


Figure 16 Message exchange and latency calculation when the Guidance control application is implemented in the Cloud

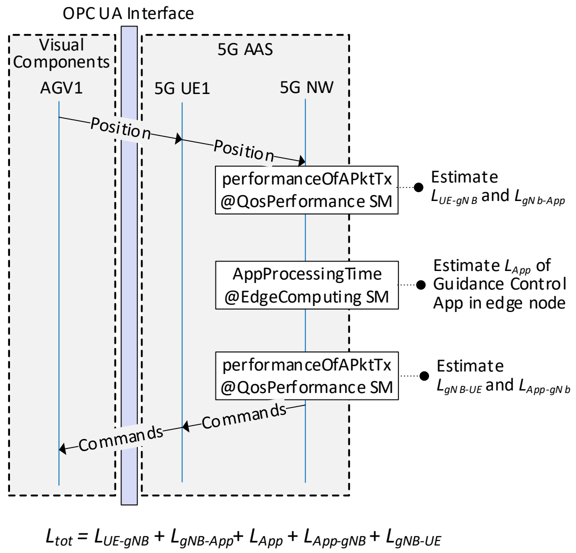


Figure 16 Message exchange and latency calculation when the Guidance control application is implemented in an edge node

- *Scenario 2 - Collision avoidance:* The position of the 5G-enabled device is continuously updated in the 5G UE AAS, and the AAS facilitates access to this data through the implemented OPC UA interface. In this case, the Collision avoidance application (that can be implemented in the Cloud or in an edge node) subscribes to periodically received information about the position of all AGVs in the scenario in the 5G AAS. The Collision avoidance application periodically checks the position of the AGVs and sends a warning if a potential collision is detected. A potential collision is decided when an AGVs is at a distance shorter than a pre-established threshold from an obstacle (an obstacle can be another AGV or any device or object). If the AGV receives the warning in time, it stops safely; otherwise, a collision occurs.

Similarly to the Guidance control application, the Collision avoidance application can be located in the Cloud or in an edge computing node. When the application is located in the Cloud, the 5G NW AAS sends the AGVs position data to the application through the Internet. If a potential collision is detected, the Collision avoidance application sends a warning message through the Internet to the AGV. In this case, we measure the real latency experienced in the transmission of the messages between the application and the gNB ($L_{gNB\text{-}App}$ and $L_{App\text{-}gNB}$), and the latency experienced in the transmission of the messages between the gNB and the AGVs is estimated in the *QosPerformance* sub model of the 5G NW AAS ($L_{gNB\text{-}App}$ and $L_{App\text{-}gNB}$). When the Collision avoidance application is implemented in an edge node, all latency components ($L_{gNB\text{-}App}$, $L_{App\text{-}gNB}$, $L_{UE\text{-}gNB}$, $L_{gNB\text{-}UE}$, and L_{App}) are estimated by the *PerformanceOfAPktTx* operation of the *QosPerformance* sub model and the *AppProcessingTime* operation of the *Edge Computing* sub model in the 5G NW AAS.

3.2.2 Testing procedure and activities

Use case 1: battery design

All the different trials within this use case follow the same procedure but differ in the battery designs. When a battery design first is in a state that makes production planning reasonable, the battery designer exports the CAD data using the CATIA add-on. This add-on will then query some basic production information from the designer, before it reads and writes the rest of the metadata. The point in time when it becomes reasonable to start this process is up to the designer.

After this process is completed, the 3DXML file can be imported to the BICs' digital twin using the automated simulation setup plugin. When executed as planned, the basic simulation of the production of this battery is ready to run. The simulation that can be monitored now is not entirely accurate due to the compromises discussed in 3.1.3, but these inaccuracies are mainly visual problems. Nevertheless, the designer must be aware of their possible occurrence.

By using the resiliency check plugin and monitoring the simulation the designer can now determine possible faults or complications during the production and afterwards evaluate if these can be eliminated by design changes.

Use case 2: process planning and optimisation

Improvement of Process planning

The trials of to test the improvement of Layout and process planning was achieved by creating an optimized workflow. Therefore, the data exchange went over cloud workspaces with automated notification messages for a defined group of people. In addition, the designed products were exported as 3DXML files this allowed an automated update of the product in the simulation. After the planner receives the notification from the shared cloud workspace the actualisation of the product in the simulation is carried out automated when opening the simulation. As the planner has more expertise, is then able to adjust the simulation and mend the last mistakes.

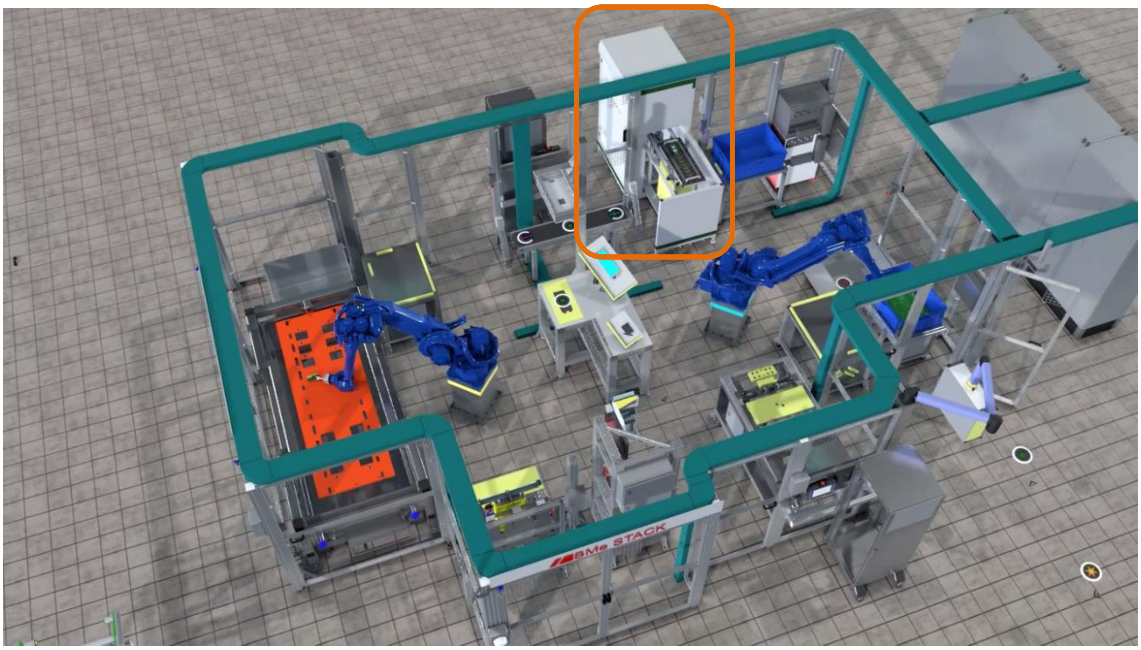


Figure 17: Trial of changing BIC layout (cell tester from presentation from GA Gurten)

Resilience metrics tool validation

The resilience testing methodology represents a systematic approach to evaluating manufacturing system adaptability through advanced simulation techniques. This comprehensive procedure encompasses multiple validation phases, technical implementation strategies, and expert evaluation processes designed to assess the robustness of production systems when faced with product variations and process modifications. The testing framework leverages Visual Components simulation technology as the primary platform for creating realistic manufacturing environments that mirror actual production conditions.

Test Environment Architecture

The testing procedure relies on three different simulation layouts build in Visual Components, each representing different aspects of modern manufacturing challenges:

1. AVL Battery Innovation Center (BIC) Simulation

The primary simulation environment replicates AVL's BIC, incorporating all critical production processes, material handling systems and quality control stations. The comprehensive digital twin captures the complexity of modern battery manufacturing, included automated assembly lines, testing stations and logistics. The simulation includes detailed representations of robotic systems, conveyors and human-machine interaction points. This allows to recreate the production of a battery in the virtual world, from the beginning till the finished product.

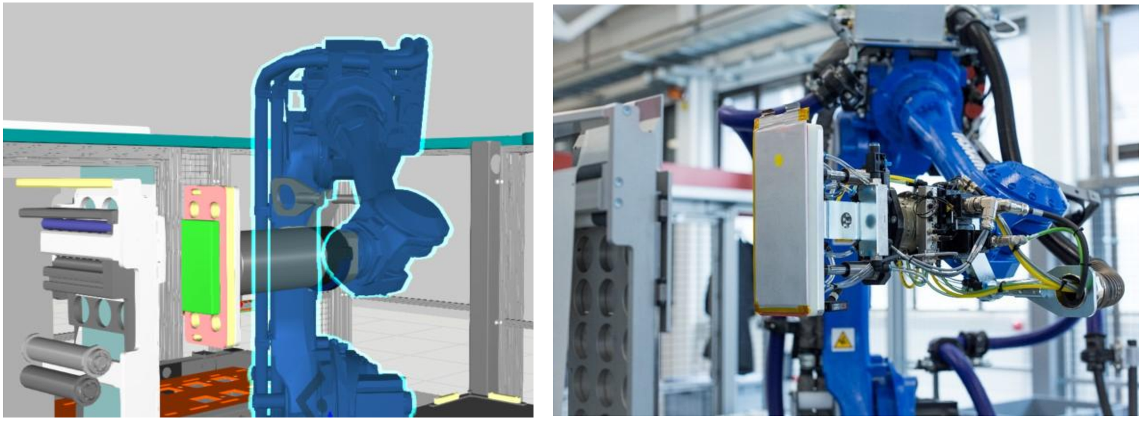


Figure 18 Comparision of digital twin and real life

2. Battery Dismantling Line Simulation

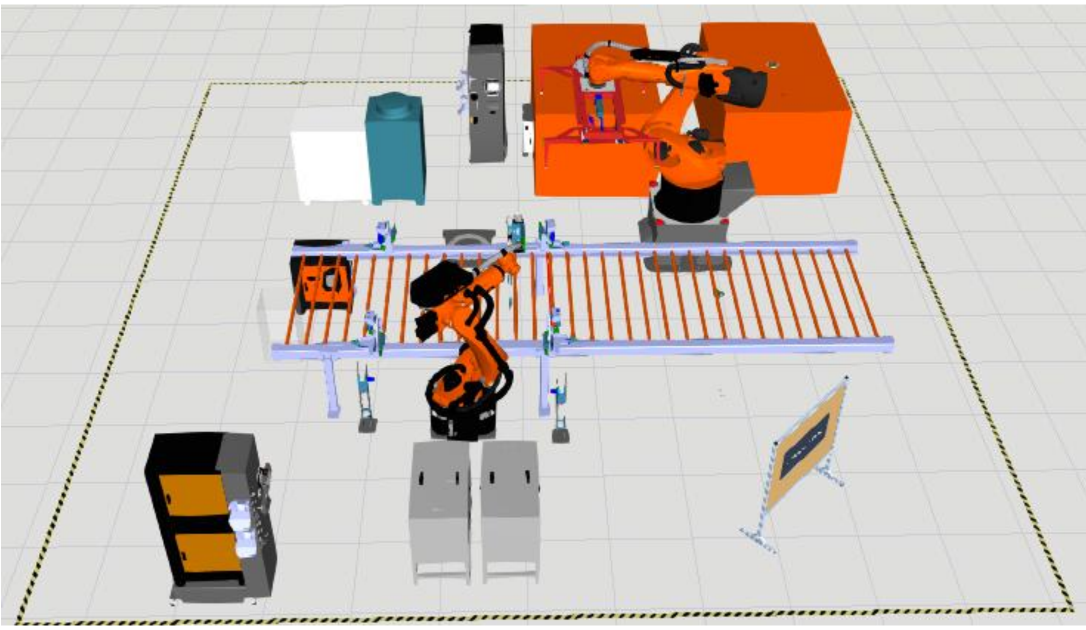


Figure 19 Battery Dismantling Line

The second simulation focuses on end-of-life battery processing the growing importance of circular economy principles in battery manufacturing. This specialized environment simulates the complex process of safely disassembling batteries form electronic vehicles. The simulation incorporates the dismantling of the mechanical structure the battery packs are stored to the removal of the individual battery pack. Industrial robotic systems with are used for this tasks that are potentially dangerous for humans.

3. DIMOFAC Pilot Line Simulation

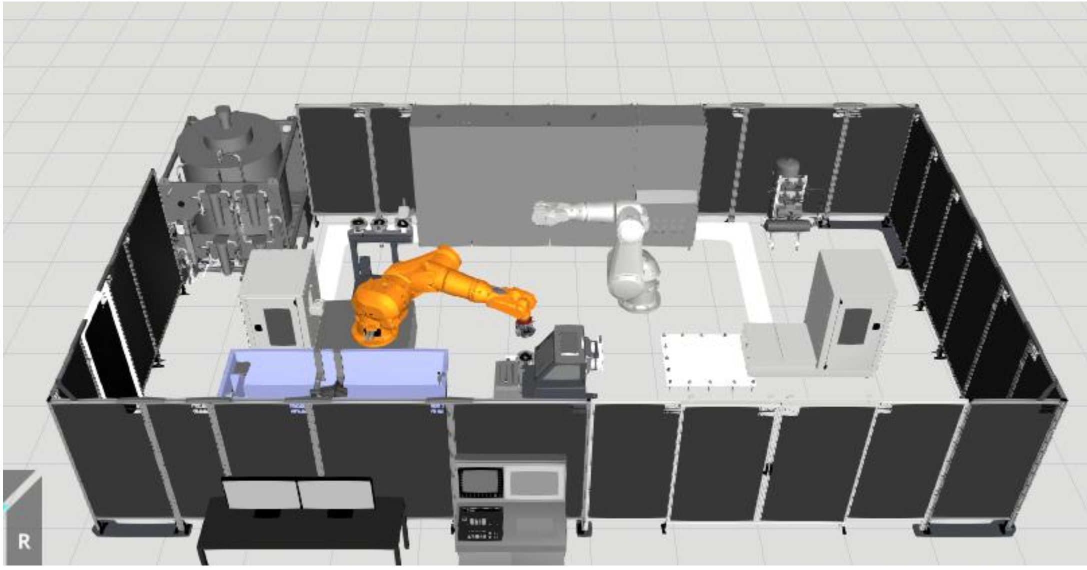


Figure 20 DIMOFAC Pilot Line

The third simulation environment utilized the DIMOFAC pilot line, located at the NC ROBO LAB within FILL's facilities. The pilot line featured a modular robotic cell capable of complete product assembly through automated tool changing capabilities. The manufactured product was a carbon fiber demonstration component. The assembly process involved joining carbon fiber subcomponents using controlled heat application and installing metallic inserts for reinforcement. The final manufacturing step included quality verification using ultrasonic testing equipment to ensure structural integrity and detect potential defects.

Technical Implementation Strategy

Phase 1: Advanced Resilience Plugin Development and Deployment
The resilience assessment begins with the systematic deployment of a specialized plugin designed to evaluate system adaptability across all three simulation environments. This sophisticated tool is based on the research done by Chalmers and expanded by a Lifecycle Cost analysis and a Failure Mode and Effects Analysis. With inputs provided by the machine manufacturer and machine user the plugin can create the desired data.

The plugin executes comprehensive product variation scenarios, systematically introducing changes in product specifications, production volumes, and process requirements. These scenarios include material substitutions, dimensional variations, quality standard modifications, and supply chain disruptions. The system measures multiple performance indicators including throughput rates, quality metrics, energy consumption patterns, and resource utilization efficiency.

Advanced analytics capabilities within the plugin generate detailed resilience metrics, providing quantitative assessments of system robustness. These metrics encompass adaptability scores, recovery time measurements, performance degradation analysis, and cost impact assessments. The plugin also incorporates sensitivity analysis capabilities, identifying which system components are most vulnerable to specific types of changes.

Phase 2: Comprehensive Validation Framework

The validation process represents a critical component of the testing procedure, ensuring that simulation results accurately reflect real-world manufacturing performance. This multi-faceted approach combines empirical data collection with advanced simulation techniques to provide robust verification of system capabilities.

Energy Consumption Validation

The energy validation process initially envisioned a sophisticated dual robotic arm configuration connected to a unified supply circuit, enabling comprehensive energy measurement capabilities. This setup would have provided real-time monitoring of energy consumption patterns, including peak demand analysis, idle time energy usage, and dynamic load variations. The system was designed to capture energy recuperation during robotic braking phases, providing insights into potential energy optimization opportunities.

However, significant technical and economic constraints necessitated a modified approach. The acquisition of two new robotic systems would have required substantial capital investment, exceeding project budget limitations. Additionally, the existing robotic infrastructure lacked energy recuperation capabilities, limiting the accuracy of energy consumption measurements. These constraints led to a strategic pivot toward alternative validation methodologies.

The implemented solution utilizes advanced offline programming simulation tools provided by leading robot manufacturers. These sophisticated software platforms incorporate detailed energy consumption models based on extensive manufacturer data and real-world testing results.

While this approach offers valuable comparative analysis capabilities, certain limitations must be acknowledged. The accuracy of manufacturer-provided simulation data remains unverified against independent measurements, potentially introducing systematic errors in energy consumption calculations. Despite these limitations, the simulation-based approach provides sufficient accuracy for initial comparative analysis and trend identification.

Cycle Time Validation

The cycle time validation process employs a comprehensive benchmarking approach, comparing simulated production cycles against extensively documented historical performance data.

Use case 3: mobile robots

The industrial plant is modelled using Visual Components, while the 5G digital model is implemented in Python using the BaSyx SDK, AASX Package Explorer, and the asyncua library to create an OPC UA server. This server facilitates communication between the 5G model, industrial model, and external applications, using XML-based AAS files for the 5G User Equipment (UE) and Network (NW).

The 5G Network AAS simulates communication reliability using Packet Delivery Ratio (PDR) curves, which depend on the distance between transmitter and receiver and the chosen Modulation and Coding Scheme (MCS). These curves are derived from simulations using the Matlab 5G Toolbox, considering an indoor factory environment with specific 5G configurations (e.g., 4 GHz frequency, 30 kHz subcarrier spacing, 20 MHz bandwidth, and non-line-of-sight conditions).

Latency is also modeled in detail, accounting for delays across the radio, transport, core, and application layers. Two deployment scenarios are considered:

- Cloud-based applications, which introduce higher latency.
- Edge-based applications, which offer lower latency due to proximity to the base station.

The three scenarios mentioned before are evaluated as follows:

- *Scenario 1.A:* AGV1 sends its position to AGV2 every second. AGV2 stops if it misses three consecutive messages and resumes after receiving five. The impact of base station location and MCS choice (MCS10 for reliability vs. MCS14 for efficiency) is analysed.
- *Scenario 1.B:* AGVs communicate with a guidance control application. If an AGV doesn't receive driving commands within a defined survival time (2–3× transmission interval), it stops. It resumes after receiving commands at the expected rate for a defined recovery period (5× interval). Transmission intervals of 200 ms and 500 ms are tested.
- *Scenario 2:* AGVs interact with a collision avoidance application. A warning is triggered when an AGV is within a certain distance of an obstacle. If latency delays the warning, a collision may occur. The warning distance is calculated based on transmission periodicity and a scaling factor.

3.2.3 Barriers faced and changes with respect to the planned activities

During the execution of the testing procedures for both battery design and process planning use cases, several practical and technical barriers emerged, leading to necessary adjustments in the originally planned activities. Generally, the complexity of the simulation environments of the BIC digital twin, the battery dismantling line and the DIMOFAC pilot line demanded more time and resources than initially anticipated. The development and deployment of the resilience plugin, although successful, required iterative adjustments to accommodate diverse product variation scenarios and ensure compatibility across all simulation applications.

Use case 1: battery design

The main barrier of this use case is the difficulty in verifying simulation results due to the nature of prototype production. Since each battery design was unique and produced in low volumes, there was limited uniform production data available for comparison. This made it challenging to validate simulation accuracy and assess the impact of design changes on manufacturability. As a result, the trials relied more qualitative evaluation and expert judgment rather than direct comparison.

Use case 2: process planning and optimisation

The high utilisation of the Battery Innovation Center posed a significant constraint. Ongoing production commitments and customer deadlines left little room for testing new processes or conducting extended trials directly at the machines, during regular operations. Additionally, technical issues like long glue curing times and the absence of shift operations introduced substantial variability in cycle times, limiting the consistency and reliability of certain datasets. However, the stacking process remained a valuable source of high-quality data. Due to information on battery cell level, a big amount of data is produced in a relatively short period of time, providing a stable reference point for simulation validation and performance analysis.

3.3 Final KPIs monitoring and validation

3.3.1 Industrial Outcomes and Lessons Learned

In general, the industrial outcome using the software architecture shows promising potential in enhancing process planning and simulation capabilities. However, it has not yet reached full maturity. While the tools demonstrate clear value in automating workflows, improving data integration and enabling more realistic production modelling, certain limitations remain. Particularly, these limitations concern usability and system robustness. The trials have revealed that although the foundation is solid, further refinement and validation are necessary to fully align the digital twin architecture with the complex and dynamic requirements of the BICs' prototype battery production. Nevertheless, the achievements in terms of supporting a more agile, data-driven and realistic production planning must not be overlooked.

Use case 1: design phase

For battery designers, the integration of the digital twin software architecture into their workflow offers valuable support in bridging the gap between design and production and enhancement in design-to-production transparency. By feeding the simulation with CAD data as already described above, designers gain visual feedback and statistics on how their battery designs are processed within the factory, within seconds. This enables a deeper understanding of production implications of their design decisions. However, with increasing complex battery designs, challenges such as longer loading times, reduced simulation accuracy and more demanding setup processes can arise. Whereas, loading times may be used for other tasks, the accuracy and the increase in setup complexity cannot be denied. Nevertheless, a personal learning process for each designer is encouraged by observing on how changes in design affect the simulated production flow. Over time, this fosters a more production-aware design approach. Looking ahead, the simulation environment may also serve as a valuable training tool for new designers, helping them to build intuition and experience by visualizing real-world manufacturing scenarios based on their own design inputs.

Use case 2: process optimisation

From a production perspective, the implementation of the digital twin software architecture into a planners' workflow marks significant advancements in planning precision, responsiveness and process transparency. By leveraging simulation tools that are directly linked to enriched CAD data, planners can visualize and validate entire production flows before physical implementation. This enables early detection of bottlenecks, inefficient sequences or resource conflicts, in a grade of detail way beyond traditional production planning tools allow. These sophisticated tools pave the way for proactive adjustment and more resilient planning.

A key advancement is the real-time synchronization between the simulation environment and the factory through connection to the SQL server ensures that the digital twin remains continuously updated with live production data, allowing planners to base the decisions on current factory rather than static assumptions.

One of the most impactful outcomes is the enriched CAD model system providing planner with a clear understanding of the designers' intent of production. This shard data foundation creates a visual and functional basis for collaboration between design and planning teams, ensuring that both sides are aligned from the earliest stages of development. As a result, discussions become more targeted and potential misunderstandings between design and manufacturing are significantly reduced.

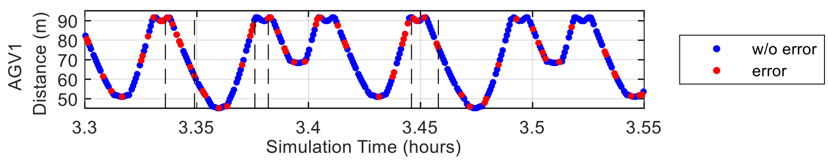
Moreover, the simulation environment acts as a digital testing platform for the further development of the BIC. Planners can test new layouts, machine configurations and process sequences without disrupting ongoing operations. This flexibility supports continuous improvement and innovation, while also enabling faster adaptation to new product requirements or production technologies.

Use case 3: mobile robots

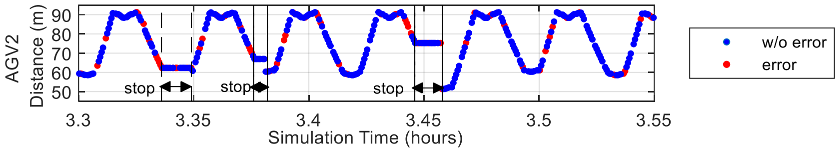
As the results of this use case are not represented by the KPIs for this pilot, the detailed results will be discussed within this section.

Guidance control (Scenario 1.A)

Figure 21 shows an example of the messages transmitted with and without (w/o) errors on the links between AGV1 and the gNB (Figure 21.a) and between the gNB and AGV2 (Figure 21.b) over 25 minutes of simulation time. The results correspond to the scenario where the gNB is located in position A and the AGVs use MCS14 for their 5G transmissions. The quality of the transmissions depends on the distance between the AGVs and the gNB, but also on the presence or not of Line-of-Sight conditions between the AGVs and the gNB. Figure 21 also identifies the time intervals during which AGV2 was stopped because there are 3 consecutive transmission errors.



a) AGV1-gNB link.



b) gNB-AGV2 link.

Figure 21. Example of the quality of 5G transmissions in the scenario.

Figure 22 shows the probability that AGV2 does not receive a message from AGV1 when using MCS10 or MCS14 for the 5G transmissions. This happens when there is a transmission error in either of the two links (AGV1-gNB and gNB-AGV2). The probability is depicted as a function of the distance of the AGVs to the gNB. The figure shows that the probability of message loss increases with the distance between the AGVs and the gNB, and the use of less robust MCS (i.e. MCS14). The highest probability of error occurs when both AGVs are at long distances to the gNB, which typically happens when the AGVs are in the pickup area if the gNB is in position A, or when both AGVs are delivering material to the production lines if the gNB is in position B. Figure 23 presents the normalized histogram of the distance of each AGV to the gNB throughout a simulation when the gNB is located in position A. The figure shows that the AGVs spend a significant percentage of time in the material pickup area (distances between 85 and 95 m). AGV1 is frequently located at distances of around 65 m and 45-50 m, which correspond to the delivery positions for lines 1 and 3. AGV2 spends a higher percentage of time at distances around 55-60 m, which corresponds to the delivery position for line 2. This results in 10.54% and 20.62% of the messages transmitted by AGV1 are not received at the AGV2 when using MCS10 and MCS14 respectively, as shown in Table 1.

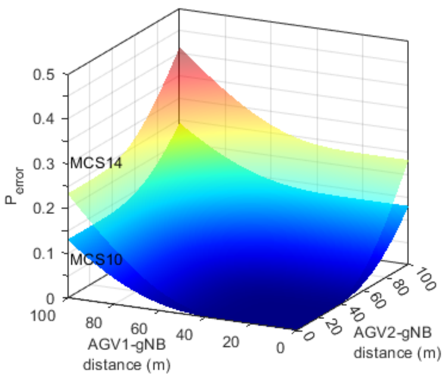


Figure 22. Probability that AGV2 does not receive a message from AGV1.

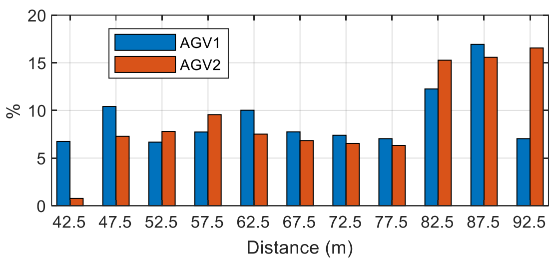


Figure 23. Percentage of time that each AGV is at a distance to the gNB.

Table 1 also shows the average time between consecutive stops of AGV2 (because it does not receive three consecutive location updates from AGV1), and the percentage of time that AGV2 is stopped during the simulation. The table shows the average time between consecutive stops of AGV2 augments when using the less robust MCS (MCS14) because of the higher 5G transmission error rates (Figure 22). This results in that AGV2 is stopped for 12.17% of the time when using MCS14 compared to just 1.24% when using MCS10. This is important because the time AGV2 is stopped impacts production, as shown in Table 2. Table 2 reports the reduction of produced items per press line and in all the plants considering the impact of 5G communications (with MCS14) compared to an ideal error-free scenario. Table 2 shows that the stops of AGV2 resulting from 5G communication errors mostly affect the third press line and reduce the number of produced items by 7.7% compared to an error-free scenario. Communication errors reduce the total production by 5.9%. Table 1 and Table 2 report results also when the gNB is at position B. This deployment reduces the percentage of messages not received at AGV2 since the AVGs spend most of the time at the pickup area, and therefore at closer distances to the gNB compared to the scenario where the gNB is at position A. This augments the average time between consecutive stops of AGV2, reduces the percentage of time that AGV2 is stopped (Table 1), and ultimately decreases the impact of 5G communication errors on the production of the press lines (Table 2). The results in Table 1 and Table 2 show that the performance of 5G communications affect the industrial workflow, and an adequate deployment of 5G communications infrastructure is important to improve the productivity of industrial plants.

Table 1. Impact of 5G Communications

gNB position	MCS	% of messages not received at AGV2	% of time AGV2 is stopped	Avg. time between stops (min)
A	10	10.54%	1.24%	25.47
	14	20.62%	12.17%	5.45
B	10	4.14%	0.14%	200
	14	9.84%	2.65%	14.63

Table 2. Reduction of produced items compared to an ideal communication Error-Free scenario

gNB position	Press Line 1	Press Line 2	Press Line 3	Total Production
A	5.5%	4.7%	7.7%	5.9%
B	2.3%	0.4%	3.8%	2.1%

Guidance control (Scenario 1.B)

In this scenario, we evaluate the impact of communication latency between AGVs and the Guidance Control application on plant productivity when the application is located in the Cloud or in the edge. Figure 24 presents the cumulative distribution function (CDF) of the round-trip latency experienced by packets transmitted between the gNB and the Guidance Control application when hosted in the Cloud. The results show that, in this case, the latency ranges between 600 and 900 ms, which is substantially higher than the latency observed when the application is deployed at the edge, where values range from 0.26 to 1.08 ms. It should be noted that these latency values exclude both the application's processing latency and the radio access latency between the AGVs and the gNB. Table 3 further confirms that the end-to-end latency between the AGVs and the Guidance Control application increases significantly when the application is implemented in the Cloud compared with its deployment at the edge.

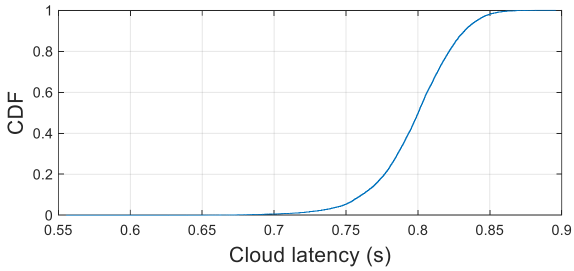


Figure 24. CDF of the latency experienced in packet transmissions between the gNB and the Guidance control application located in the Cloud (round-trip latency).

Table 3. Total latency experienced in the 5G communications between the AGVs and the Guidance control application.

Guidance control application location	Average latency	90th percentile of the latency
Edge	115.1 ms	118.0 ms
Cloud	909.2 ms	922.5 ms

Table 4 presents the impact of communication latency on the operation of AGV2. The results indicate that when the Guidance Control application is deployed in the Cloud, the percentage of time that AGV2 remains stopped during the simulation increases compared with the case where the application is implemented at the edge. This behavior arises because the interval between the reception of two consecutive packets becomes longer due to the higher latency in the communication between the AGVs and the Guidance Control application, exceeding the predefined *survival time* threshold more frequently. The results further show that a stricter *survival time* constraint requires lower latency levels to ensure proper AGV operation. This effect is also evident in Table 5. Reduction of produced items compared to an ideal scenario with zero-latency and error-free communication.Table 5. The results further show that a stricter *survival time* constraint requires lower latency levels to ensure proper AGV operation. This effect is also evident in Table 5, which reports the reduction in the number of produced items compared with an ideal scenario with zero-latency and error-free communication. The results in Table 4 and Table 5 highlight that the lower latency achieved when the application is deployed at an edge node reduces the time AGVs remain idle, thereby minimizing the overall impact on plant production. As shown in Table 5, the produced items decrease by 21.87% and 17.99% for message periodicities of 200 and 500 ms, respectively, when the survival time is set to twice the periodicity and the Guidance control application is hosted in the Cloud. In contrast, when the application is deployed at the edge close to the gNB, production is reduced by only 0.8% and 5.02% for the same periodicities.

Table 4. Impact of experienced 5G communication latency on AGV2 operation.

Guidance control application location	Periodicity (ms)	Survival Time (ms)	% of time AGV2 is stopped	Avg. time between stops (s)

Edge	200	400	8.57	10.97
		600	0.41	247.2
	500	1000	6.74	36.2
		1500	0.37	539.31
Cloud	200	400	19.76	4.83
		600	1.95	51.38
	500	1000	19.92	12.21
		1500	1.25	204.55

Table 5. Reduction of produced items compared to an ideal scenario with zero-latency and error-free communication.

Guidance control application location	Periodicity (ms)	Survival Time (ms)	Press Line 1	Press Line 2	Press Line 3	Total Production
Edge	200	400	1.14	0.84	0.50	0.80
		600	0.73	0.83	0.42	0.66
	500	1000	3.77	4.20	7.09	5.02
		1500	0.76	0.19	6.53	1.66
Cloud	200	400	22.03	22.86	21.00	21.97
		600	0.08	4.98	6.67	3.91
	500	1000	17.12	19.10	17.77	17.99
		1500	4.10	1.44	3.03	2.86

Collision avoidance (Scenario 2)

To evaluate the probability of collision in this scenario, we simulated the appearance of obstacles at random positions within the environment, thereby generating a large number of situations in which the Collision Avoidance application must detect a potential collision and send a warning message to the AGV.

Table 6 presents the percentage of cases in which the AGV collides with the obstacle. As shown, between 34.78% and 16.57% of evaluated situations result in a collision when the application is hosted in the Cloud and the warning distance is set between 1.5 and 3 times the periodicity with which the AGV's position is reported from the 5G NW AAS to the Collision Avoidance application; the percentage of collisions decreases when the warning distance increases. In contrast, when the application is deployed at an edge node close to the gNB, the percentage of collisions decreases by between 49.8% and 83.70%. When the warning distance equals three times periodicity, the percentage of situations that result in a collision is as low as 2.7%. This reduction is due to the lower latency in communication between the AGVs and the Collision Avoidance application. Lower communication latency enables the use of shorter warning distances. It is important to note that longer warning distances may cause the AGV to stop while it is still far from the obstacle. In such cases, the warning message—and the consequent stop command—may be unnecessarily triggered if the AGV had already detected the obstacle or had planned a trajectory adjustment.

Table 6.Percentage of collisions in the scenario (periodicity = 500 ms).

Warning distance	Percentage of collisions	
	Edge	Cloud
1.5 · periodicity	17.46%	34.78%
2 · periodicity	5.33%	27.39%
2.5 · periodicity	4.31%	17.19%
3 · periodicity	2.7%	16.57%

Generally, the results consistently demonstrate that network planning and deployment and application placement have a decisive effect on both operational reliability and factory productivity. The results achieved in the evaluated scenarios have demonstrated the importance and need to integrate 5G and industrial digital models, and the value of the integrated SW platform developed for the efficient joint planning and dimensioning of industrial processes and 5G networks.

3.3.2 KPI Measurement and Performance Evaluation

ID	BUSINESS Indicators	DESCRIPTION	Unit	Initial value	Expected final Value	Expected Date of achievement
1	O1.1	Time to adapt to product change reduction	%	6 h	-30%	End of implementation
2	O1.2	Time to market – Lot-size-1 engineering	%	N/A	-15%	End of implementation
3	O1.3	Less time designing new solutions	%	N/A	-15%	End of implementation
4	O2.1	Energy and resource efficiency increase	%	681 kWh	15%	End of implementation
5	O2.2	Safety of workers - Zero emissions, zero overwork, zero injuries	-	N/A	-	Before 24 months after implementation
6	O3.1	Reduce time to plan customized production lines with resilient planning	%	6 months (including testing)	-10%	Before 12 months after implementation
7	O3.2	Battery package optimization time	%	N/A	-15%	End of implementation

8	O4.1	Service cost reduction	%	confidential	-15%	Before 12 months after implementation
9	O4.2	Reduction of rejects	%	21,3% reject rate	-10%	Before 12 months after implementation

The KPIs of this Pilot can categorised in the following four business capabilities:

- BC1: Agility
- BC2: Sustainability
- BC3: Customisation
- BC4: Productivity

Whereas AVL focused most on the agility part, FILL was invested more in the productivity and sustainability targets. The cooperation of these two companies enabled a holistic approach to the subject. The measurement of the KPIs was for some more trivial than others. Some are not directly measurable. In order to get values despite this fact of a lack of measurability. Employees working on the trials where questioned.

Time to adapt to product change reduction - The time required to adapt to product changes is measured by comparing the production planners' estimated setup time with the actual time taken by the automated simulation setup. Fully developed modules are used to benchmark loading times, because batteries still in development show reduced loading durations depending on the number of components and fully production planning is pointless. Therefore, this KPI has been measured on a module, developed some time ago, that is based on twelve prismatic cells and also was used before implementing the software, for basic tests.

Time to market – Lot-size-1 engineering - As every new development has its own difficulties and development times are not really comparable, designers and planners were surveyed to assess how the software architecture has influenced their ability to deliver single-unit or prototype products more quickly. Their feedback provides qualitative insight into improvements in responsiveness and workflow efficiency.

Less time designing new solutions – Again asking AVLs design specialists to reflect on how the integration of the software architecture has impacted the time spent on developing new battery solutions, have been figured as best data source for evaluating the reduction of in design iteration cycles and overall design effort.

Energy and resource efficiency increase – The energy efficiency gains are measured by comparing energy consumption data collected during trials with and without optimisation of robot movements.

Safety of workers - Zero emissions, zero overwork, zero injuries – Worker safety is assessed by quantifying overwork, as most injuries are linked to excessive workload and emissions are already minimised through localised suction systems. Simulations of the production allow to collect data of a worker's movements like travelling distance or RULA-scores (Rapid Upper Limb Assessment) to address ergonomics. However, reducing the workload through better planning is a slow process. Therefore, the results will only be apparent in the long term.

Reduce time to plan customized production lines with resilient planning – The time reduction when planning new production lines was evaluated by comparing planners' initial time estimates for complex analysis (without simulation) with the time required to configure new production lines in the simulation. A newly developed optical cell tester that should be integrated into the BICs' layout was used as the example for the measurement of this KPI, leading to relatively high initial value.

Battery package optimization time – Again, as every individual optimisation process is different, the people working on this topic with the help of the new software architecture were questioned on how the software architecture has influenced their battery optimisation process.

Service cost reduction – While initial observations suggest potential cost savings, more time and data are needed to fully verify the impact of the software on service-related expenses.

Reduction of rejects – Reject rates are measured by comparing the number of rejects at the end-of-line testing before and after implementation for a certain period of time, but again the different batteries produced effect these values and therefore accuracy.

3.3.3 Final KPI Assessment and Business Impact

ID	BUSINESS Indicators	DESCRIPTION	Unit	Initial value	Expected final Value	Expected Date of achievement	Current KPI Assessment
1	O1.1	Time to adapt to product change reduction	%	6 h	-30%	End of implementation	-32,2%
2	O1.2	Time to market – Lot-size-1 engineering	%	N/A	-15%	End of implementation	-15% to -20%
3	O1.3	Less time designing new solutions	%	N/A	-15%	Before 12 months after implementation	-5% to -10%
4	O2.1	Energy and resource	%	681 kWh	15%	End of implementation	19% to 24%

		efficiency increase					
5	O2.2	Safety of workers - Zero emissions, zero overwork, zero injuries	-	N/A	-	Before 24 months after implementation	N/A
6	O3.1	Reduce time to plan customized production lines with resilient planning	%	6 months (including testing)	-10%	Before 12 months after implementation	-20%
7	O3.2	Battery package optimization time	%	N/A	-15%	End of implementation	0% to -20%
8	O4.1	Service cost reduction	%	confidential	-15%	Before 24 months after implementation	N/A
9	O4.2	Reduction of rejects	%	21,3% reject rate	-10%	Before 12 months after implementation	-4,5%

The implementation of the digital twin software architecture has introduced a new level of transparency efficiency and adaptability to battery production planning and design workflow. Whereas the KPIs evaluated within this section mainly focus on time related improvements, it must not be forgotten, that the architecture used in this pilot supports a general increase in quality of AVL products. RE4DY Tools help AVL to stay in position of a top-notch battery developer especially in terms of fast and high-quality development, as well as CO_2 neutral production.

Time to adapt to product change reduction – The implementation of the automated simulation setup significantly reduces the time required to adapt production plans to new battery designs. For the fully developed module that was used for KPI assessment, the automated setup took approximately 3 minutes and 53 seconds. This value has also been compared with more and less complex designs. While less complex modules sometimes were processed in under one minute, more sophisticated designs could take about 5 minutes. The time needed to set up the simulation manually to a comparable state, was estimated at 2 hours for a medium-experienced planner. This time also varies depending on the battery's complexity and the planners' know-how, but due to time-consuming tasks such as defining patterns for stacking and the shipment boxes, as well as programming for welding and gluing robots, 2 hours were considered realistic. The whole planning process within the simulation was considered to normally take about 6 hours as refining and optimising takes its time. As the automated setup results in time savings of about 116 minutes, the time savings equate to 32.2%.

Time to market – Lot-size-1 engineering – The software architecture supports faster delivery of prototype and single-unit products by streamlining communication and reducing iteration cycles. Fewer and better-aligned consulting between designers and planners, combined with resiliency check software and automated simulation setup, enable quicker validation of design changes. Based on expert estimates and the principle of the rule of ten, the overall time savings are expected to be between 15% and 20%.

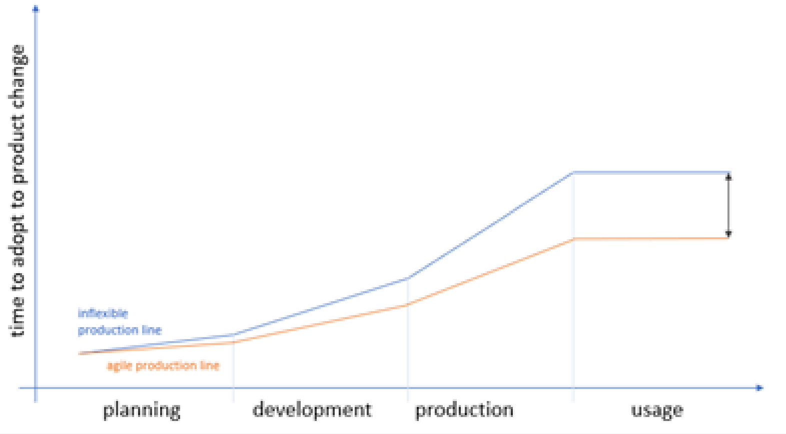


Figure 25 Product change time

Less time designing new solutions – Battery designers reported a noticeable improvement in their workflow efficiency following the implementation of the software architecture. Depending on the complexity of the battery design, estimated time savings range between 5% and 10%, primarily due to faster feedback from simulations and reduced need for manual adjustment.

Energy and resource efficiency increase – Energy and resource efficiency are measured by comparing consumption data collected during simulation trials before and after process optimisation. The energy consumption could be reduced by ~19% by removing the battery pouches from the box, applying glue and stacking them at the transport station. Initially, the energy consumption of the cell was around 681 kWh; after optimisation, this figure fell to 552 kWh. However, the cycle time could also be reduced by optimising the robot programme in the simulation. This was achieved by removing unnecessary movements from the programme. The initial cycle time of 223 seconds could be improved to 211 seconds, an improvement of ~5%. The target efficiency increase of 15% was easily achieved by only increasing energy efficiency. When combining the decrease in energy consumption and the reduction in cycle time for emptying a box of battery pouches, the overall efficiency of the cell results in an improvement of ~24%. As the results are obtained through simulation, it is possible that the values may differ slightly from reality.

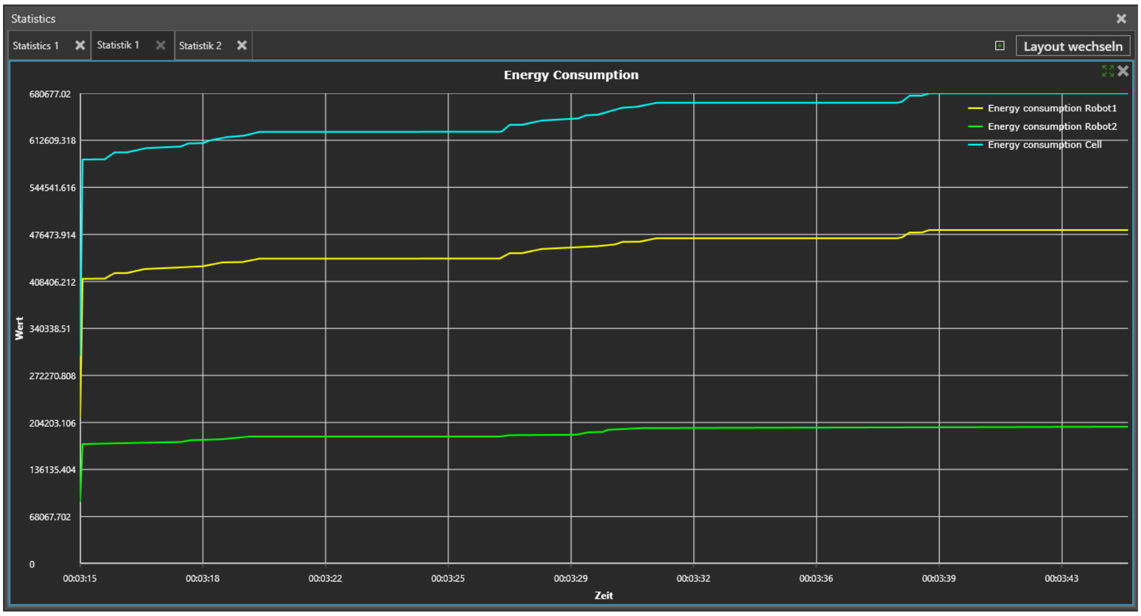


Figure 26 Energy consumption before optimisation

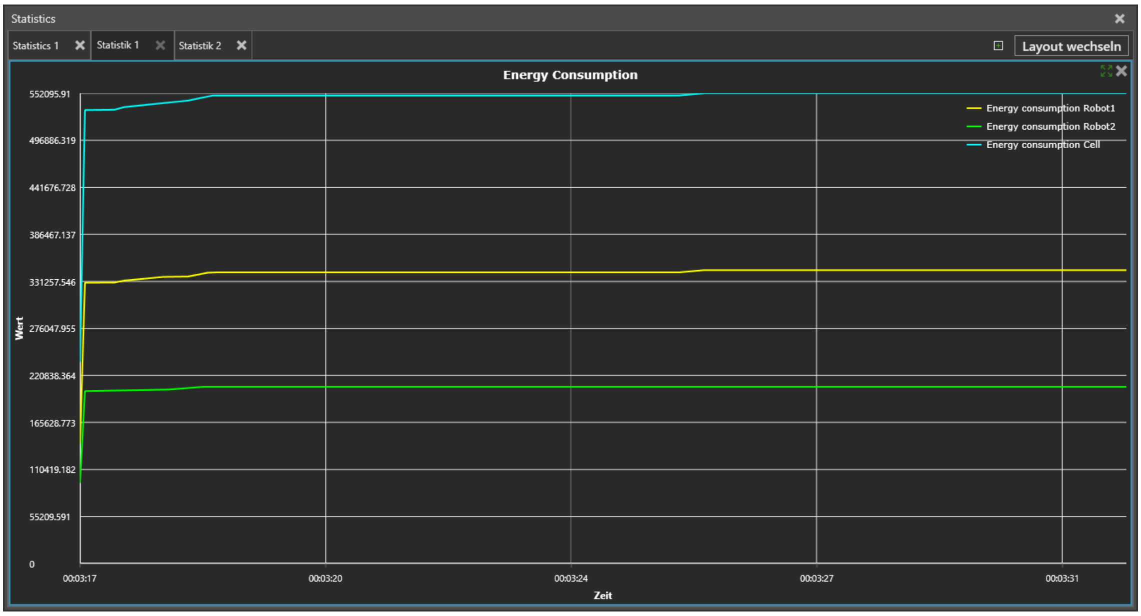


Figure 27 Energy consumption after optimisation

Safety of workers - Zero emissions, zero overwork, zero injuries – While the architecture supports safer working conditions using simulation-based planning to prevent temporary overwork, reliable quantitative data is not yet available due to the short observation period. Analysing working conditions using the RULA method provided valuable insights. However, as the BICs workplaces were already designed with ergonomics in mind, there was little room for improvement. Nevertheless, using this tool when developing new machines or processes for production enables the proactive implementation of measures to ensure a safe, ergonomic workspace.

Reduce time to plan customized production lines with resilient planning – By integrating models of new machines in the digital twin environment, the planning accuracy has improved significantly. The main impact on the time is that accurate planning can be done before a prototype machine is built, allowing to save crucial time and money as bottlenecks can be found earlier and more easily. On the other hand, it must be said that creating a model for the machine can be time consuming as well. Nevertheless, planners working on the integration of an optical tester for battery cells, pointed out that since using the digital twin approach, work efficiency increased enormously, especially at the end of the planning phase. Therefore, the time reduction was estimated at around 20%.

Battery package optimization time – Designers estimated a 20% reduction in optimisation time when the focus is on manufacturability. However, when optimisation targets other aspects such as performance or cost, this number drops. Considering performance optimisation, the time savings are negligible and for cost tweaks the numbers are also just about 10%. Nevertheless, the simulation environment helps streamline manufacturability assessments and support faster iteration.

Service cost reduction – While long-term data is still being collected, early indications suggest that proactive planning and predictive simulation contribute to reduced service costs. The full impact will become clearer over time as more operational data is analysed.

Reduction of rejects – A comparison of production data over two similar three-month periods shows a reduction in reject rates. In the recent period, 24 issues occurred among 119 modules that have been produced without problems, resulting in a 16,8% reject rate. Previously, 88 issues were recorded among 324 modules, leading to a 21,3% reject rate. This improvement of 4,5% reflects the positive impact of simulation-based planning and early fault detection.

The KPI assessment demonstrates that the implementation of the digital twin software architecture has led to measurable improvements across several key areas of battery production planning and design. Although, some of the KPIs were not completely met or were difficult to measure, the achievements during this project are not negotiable. The collaboration between AVL and FILL has laid the groundwork for a robust and scalable solution and with continued development and validation, the architecture is well-positioned to become a key enabler of efficient and resilient manufacturing processes.

4 Performance Monitoring Framework

4.1 Introduction of methodology (6P-Performance Pillar)

The 6Ps Migration Model is a strategic maturity framework for manufacturing that assesses a company's current and target digitalization across six pillars: Product, Process, Platform, People, Partnership, and Performance. Balancing technical and socio-business dimensions. It supports two situations: organizations already running digital projects (where it tracks progress and impact) and those that have identified gaps but not yet acted (where it guides prioritization).

Task 4.4 focuses on the Performance pillar, evaluating how indicators are defined, measured, and monitored—not whether values improved—across six areas: Operational/Technical, Economic, Environmental, Social, Product-Service Lifecycle, and Supply Chain. Maturity is rated on a five-level scale from "Initial" to "Exploited", enabling standardized, comparable assessments across pilot sites and facilitating generalization of impact KPIs beyond single factories. The model flexibly incorporates technical elements—process planning, data sharing/integration, federated learning and AI, and integration progress—so performance monitoring aligns with work-package goals.

A survey instrument is structured into sections on pilot business processes, data sharing and the Data Container (including benefits like data-driven decisions), AI/FL adoption and effectiveness, and integration achievements such as data synchronization and digital twins. The methodology follows five steps: design the survey, determine the AS-IS profile, define the TO-BE profile, identify actions to bridge gaps, and assess progress via end-of-project interviews. Overall, the approach does not directly evaluate KPI outcomes; instead, it measures the maturity and robustness of performance management practices along the digital transformation journey.

For a more detailed overview of the 6P methodology (Performance Pillar), please refer to D5.3.

4.2 Analysis of the Performance Pillar (AS-IS) – Survey

This section presents an analysis of the first iteration of survey responses (Annex 1), The primary objective of this survey is to capture the initial state (As-Is) of digital and organizational maturity within the manufacturing enterprise, while also identifying their future expectations (expected To-Be) and targeted development goals.

Following sections represent collected responses from the two main pilots under WP5 AVL+FILL and VWAE. For the remaining two pilots, AVIO and GF, relevant information can be found in Deliverable D5.3.

As outlined earlier, the analysis is divided into two main components. The first focuses on the six core aspects of the Performance dimension, offering an interpretation of responses related to each area. The second addresses the additional questions that were specifically developed to align with the project and work package requirements, along with their corresponding analysis and interpretation.

4.2.1 Electric-Battery Production Systems (AVL) AS-IS

Table 7. summary of the results from the 1st iteration AVL

Performance Dimension	AS-IS	TO-BE
Operational - Technical	Initial	Exploited
Economic	Defined	Exploited
Environmental	Defined	Exploited
Social	Defined	Exploited
Product-Service Lifecycle	Exploited	Exploited
Supply Chain	Managed	Integrated

The Operational-Technical dimension, is at “Initial” in the AS-IS, with a TO-BE of Exploited. This means that, at baseline, measurement and improvement practices exist only in a rudimentary or ad-hoc form around the pilot scope, which is consistent with the survey narrative that the main process has been defined, and a first end-to-end process flow was tested, while integration into the existing IT and process landscape remains a constraint. The TO-BE of “Exploited” sets the ambition for mature, data-driven and continuously optimized operation, implying predictive and prescriptive capabilities embedded into day-to-day work.

Economic is at “Defined” in the AS-IS, with a TO-BE of “Exploited”. This places AVL’s baseline as having explicit, documented procedures and agreed metrics for economic performance around the pilot, but not yet the fully automated, closed-loop cost optimization that an “Exploited” state would entail. The direction of travel is toward systematic cost transparency and proactive optimization tied to planning and execution, which aligns with the stated goal of hardening integration and moving from a first validated flow into sustainable operation.

Environmental is at “Defined” in the AS-IS, with a TO-BE of “Exploited”. Practically, this indicates that environmental KPIs and procedures are formalized but not yet exploited for continuous improvement at the level of automated monitoring, design-for-environment feedback loops, or scenario optimization. The forward target implies expanding beyond documented indicators to active use of environmental data in decision making across design, planning and execution.

Social is at "Defined" in the AS-IS, with a TO-BE of "Exploited". This reflects a baseline where social-domain processes and indicators are specified but not yet leveraged in a closed-loop manner to drive improvements in training, ergonomics or workforce well-being linked to the pilot. Moving to Exploited will require systematic capture and use of social performance signals alongside operational and quality signals, feeding back into planning and training.

Product-Service Lifecycle is already at "Exploited" in the AS-IS, with a TO-BE that remains "Exploited". This confirms that AVL has lifecycle practices at a mature level for the pilot scope, such as LCC and LCA being actively used rather than merely documented and potentially complemented by broader lifecycle insights in planning and evaluation. Maintaining "Exploited" as the target suggests the focus is on sustaining and extending these practices as integration improves, not on changing their maturity level.

Supply Chain is at "Managed" in the AS-IS, with a TO-BE of Integrated. "Managed" denotes that supply-chain performance is measured and controlled with established procedures, data and review rhythms, but that end-to-end interoperability, cross-system synchronization and partner-level alignment are not yet seamless. Integrated as the objective signals a move toward connected data flows and unified KPI computation across internal systems and relevant partners, which is coherent with the challenges reported around integrating the pilot into the current IT and process landscape.

Taken together, these confirmed maturity selections refine the earlier interpretation of the baseline. The pilot stands on a foundation where the core process has been defined and a first process flow has been tested, while several dimensions remain at early to mid-levels of maturity due to integration hurdles. The targets consistently point to an Exploited end state across operational-technical, economic, environmental and social dimensions, to maintain an already Exploited lifecycle practice, and to advancing supply chain from a controlled internal posture to a genuinely integrated one. This trajectory underlines the centrality of completing integration into the legacy IT and process environment so that defined practices can be elevated into exploited, closed-loop routines and so that supply-chain KPIs can be computed and acted upon across systems rather than within silos.

Pilot business processes: The progress in achieving objectives for process planning and preparation is rated Good in Q14. This refines the earlier interpretation based on free-text milestones, confirming that AVL had defined the main process and completed a first end-to-end process-flow test and views the status as solid rather than tentative. The original free-text note about unforeseeable difficulties integrating into the existing IT infrastructure explains why the Operational-Technical dimension is still Initial at baseline, but the explicit good rating clarifies that, despite those hurdles, process-planning progress is positive at AS-IS

Data Sharing and Integration: Q15 reports Average progress. The specific challenge identified in Q18 is Lack of resources or expertise, while the effectiveness of the data container itself is rated Neutral in Q19 and the benefit most clearly perceived in Q20 is the Ability to implement new digital services. Taken together, this positions the AS-IS as one where the integration fabric is in place and enabling new services, but depth and pace are constrained by limited specialist capacity; the container's current impact on exchange and service enablement is viewed neither positively nor negatively overall, despite the concrete benefit observed.

AI Models and Federated Learning: Q22 indicates Average progress and Q23 rates effectiveness as Neutral, with Q24 selecting Improved model accuracy as the realised benefit and Q25 reporting No challenges faced. This combination updates the baseline from tentative to moderately active: federated learning is being leveraged to a degree that is sufficient to yield accuracy gains in at least one model context, is not yet judged clearly effective or ineffective overall, and has not encountered material obstacles during implementation. In AS-IS terms, this supports the Economic and Operational-Technical TO-BE ambitions by evidencing some technical traction, even though the organisation has not yet converted that traction into clearly perceived business effectiveness.

Progress in Integration: Q27 rates overall progress as Good. Q28 flags two concrete achievements that are now part of the baseline: Development of digital twins for tools and machines and Completion of significant data synchronisation tasks. Q30 reports No significant challenges faced in implementing the pilot at site level. These results nuance the earlier narrative that emphasised integration difficulties: the free-text comment captured earlier reflects initial friction during set-up, whereas the scored items now show that, by the time of this AS-IS capture, the site considered integration progress good, had accomplished substantial synchronisation work and digital-twin development, and did not perceive unresolved obstacles as significant. This resolves the apparent contradiction by placing the earlier difficulties as start-up issues that have been addressed to a point where they no longer register as major challenges.

Synthesizing these updates, the AS-IS for AVL is a baseline with Good progress in process planning and in integrating reference-architecture components, Average progress on data-sharing and federated-learning strands, a Neutral present-tense view of both the data container's effectiveness and federated-learning effectiveness, and tangible benefits already visible in the ability to implement new digital services and in improved model accuracy. The capability profile aligns with the maturity table: lifecycle practices are already exploited, supply-chain monitoring is managed and moving toward integration, and operational-technical practice is still at an initial stage because the present setup has not yet crossed into predictive or prescriptive routine operation. The absence of significant current challenges at site level, together with the completed synchronization tasks and digital-twin development, suggests that the principal AS-IS limiting factor is capacity rather than feasibility, which is consistent with the Q18 selection noting a lack of resources or expertise as the outstanding integration constraint.

4.2.2 Connected Logistics (VWAE) AS-IS

Performance Dimension	AS-IS	TO-BE
Operational - Technical	Initial	Integrated
Economic	N.A.	N.A.
Environmental	N.A.	N.A.
Social	N.A.	N.A.
Product-Service Lifecycle	N.A.	N.A.

Supply Chain	Managed	Integrated

The AS-IS baseline for VWAE is anchored to the confirmed maturity selections and the completed responses to Q14–Q30. For the performance dimensions, Operational-Technical is Initial at baseline with a TO-BE of Integrated, Economic is Not Applicable at this stage, Environmental is Not Applicable, Social is Not Applicable, Product-Service Lifecycle is Not Applicable, and Supply Chain is Managed with a TO-BE of Integrated. This establishes an AS-IS scope focused on operational logistics and supply-chain execution, where day-one operational practice is largely ad-hoc and non-predictive but the target is to institutionalize an integrated, model-driven routine; supply-chain monitoring is controlled at baseline and aims to become end-to-end interoperable and jointly governed across data owners and systems. The survey instrument and its definitions frame these levels and provide the context for interpreting the selections.

Pilot business processes: The progress in achieving objectives for process planning and preparation is rated Good in Q14. The free-text milestones reported in the survey explain why this rating is justified: the site has integrated data systems down to the shop floor, consolidated silos from previous EU projects, and is moving toward a scenario where future logistics configurations are directly available to the shop floor via analytics and simulations, supported by infrastructure already deployed locally to provide real-time information for configuration rollout. These details clarify that the AS-IS planning baseline is technically enabled and operationally meaningful even though the operational-technical maturity selection remains Initial because predictive and prescriptive routines are not yet embedded. The principal challenge noted for this strand is not hardware or software but the availability of human resources with the skills to disseminate and sustain simulation technology; because this capability is relatively new in the plant, maintaining momentum is difficult without the right personnel. Together these points characterize an AS-IS that is promising in capability yet capacity constrained.

Data Sharing and Integration: Q15 is rated progress. The main impediment selected in Q18 is lack of resources or expertise, which aligns with the planning challenge and indicates that integration depth and cadence depend more on specialist availability than on missing technology. The overall effectiveness of the data container is rated Neutral in Q19, while the clearest realised benefit in Q20 is enhanced data-driven decision making. This combination positions the AS-IS as one where the platform is already enabling better decisions through fresher, more coherent data even if it is not yet perceived as a clear differentiator in its own right, with progress gated by the specialist capacity needed to scale and harden integrations.

AI Models and Federated Learning: Q22 indicates Good progress and Q23 rates federated learning as Somewhat effective. The benefit selected in Q24 is improved model accuracy, and Q25 identifies lack of expertise as the prevailing challenge. This describes an AS-IS in which model development and deployment are underway with measurable accuracy gains, and federated learning is contributing positively without yet reaching decisive effectiveness; again, the limiting factor is skills rather than infrastructure or data access.

Progress in Integration: Overall progress is rated Good in Q27. Q28 lists two concrete achievements that now form part of the AS-IS baseline: successful connection of data sources to the data container and development of digital twins for tools and machines.

Q30 reports insufficient resources or expertise as the main roadblock at site level. These answers reconcile with the qualitative narrative by showing that initial start-up frictions have been addressed to the point where integration is progressing well and key building blocks are in place, while the governing constraint remains the availability of skilled personnel to sustain simulation and advanced analytics practices at the pace the plant wants.

Synthesising these updates, the VWAE AS-IS is marked by good progress in process planning and component integration, a managed and controlled approach to supply-chain performance that is heading toward integration, and active AI workstreams where federated learning is somewhat effective and already improving accuracy. The data container is perceived as neutral in overall effectiveness while clearly enabling enhanced data-driven decision making, which suggests that the benefits are being realised at the application and decision layers even if the platform layer has not yet been re-evaluated as strategically differentiating. Across strands, the central limiting factor is insufficient resources or expertise, which explains why operational-technical maturity is still "Initial" despite solid planning achievements and why several performance dimensions remain out of scope for the pilot's present measurement envelope. As a result, the AS-IS points to a clear operational path to the TO-BE: maintain and expand the local infrastructure that brings configurations and analytics to the shop floor, deepen container-based integrations already underway, continue federated-learning deployments that are improving accuracy, and prioritise the recruitment and retention of the specialised skills required to sustain simulation and data-driven operations as routine plant practice.

4.3 Analysis of the Performance Pillar (TO-BE) – Interview

This section presents a consolidation of the performance outcomes from its two operational pilot use-cases: VWAE (connected logistics) and AVL (electric-battery production systems). These interviews were structured to extend the mid-term analysis presented in Deliverable D4.2, capturing both quantitative KPI data and qualitative insights into process improvements, resilience strategies, and longer-term impact. By reflecting on real-world implementation experiences, our goal is to demonstrate how RE4DY has enabled the shift from automated operations toward autonomous, data-driven decision-making, and the extent to which this shift has increased operational agility, sustainability, and resilience across pilot sites. The resulting findings will offer a comparative benchmarks and strategic recommendations for future adoption across EU-wide industrial contexts.

4.3.1 Electric-Battery Production Systems (AVL) TO-BE

Pilot business processes: The to-be state formalises the current use of the production-simulation digital twin earlier in the design-to-production flow so designers can preview manufacturability issues before hand-off and reduce the number and duration of iteration loops. The interview confirms that simulation has already shortened planning cycles and improved agility; the goal now is to institutionalise this designer-accessible simulation as standard practice across prototype work so cycle-time gains are predictable and measured, not ad-hoc. In parallel, AVL is using an energy-consumption simulation to understand process energy use and to prepare for battery-passport obligations by tracking energy per pack; the to-be is to integrate these energy insights into routine planning and reporting so improvements are evidenced in KPIs rather than perceived qualitatively. Usability feedback from shop-floor users indicates the current interfaces are not easy to use; the to-be condition therefore includes simplifying interactions around existing workflows so non-experts can operate the tools with minimal confusion and the agility gains translate into everyday practice.

Data sharing and integration: Early in the pilot, AVL struggled to identify a useful data-sharing scope and therefore limited exchanges mainly to CAD and a small set of metadata; richer production data remained largely untouched. The to-be direction is to close the digital thread by linking production time series, operation steps, and part identifiers so both the twin and monitoring can consume consistent, traceable inputs. Today's collection relies on a service-based pipeline and monitoring with Power BI dashboards fed from an in-house server, but interviews report data-quality gaps, including missing or wrong values, which undermine analysis. The to-be target is a governed pipeline with basic completeness and range checks, a documented lineage from source systems to the "trusted" monitoring layer, and curated reference datasets for the twin and KPI back-testing so model validation and performance reporting do not depend on opportunistic extracts.

AI models and federated learning: AVL states that AI from RE4DY has not been materially used in this pilot, which explains neutral effectiveness ratings and the absence of significant challenges. The to-be stance is therefore staged: first, secure clean, linked production data and a stable simulation-driven workflow; second, prototype a centralised baseline model on a curated reference dataset; third, evaluate whether federated learning adds measurable value without complicating data handling. This sequencing avoids investing in training architectures before inputs are trustworthy and targets AI work where accuracy gains directly support the planning and energy-tracking needs already identified.

Progress in integration and reference architecture: Integration is assessed as good in the survey follow-up, with two concrete achievements already in use: the digital twin for production simulation and data synchronisation that feeds the twin with elements of the production plan from an SQL server, making simulations more accurate and capable of predicting likely faults such as broken cells. At the same time, AVL could enumerate some RE4DY reference-architecture layers and building blocks deployed, indicating an implicit rather than codified mapping. The to-be path is to standardise and version the data link from planning to simulation, monitor it for reliability, expand the production-data scope as the digital thread closes, and capture the component-to-layer mapping in internal playbooks so the approach is portable and less dependent on individual memory.

Comparison with initial AS-IS: The earlier survey evidence and interview remarks paint an AS-IS where process planning progress was already rated good but operational-technical practice remained at an early stage due to integration and data-quality constraints; data-container effectiveness was viewed as neutral and the "data as a product" concept was not considered applicable to AVL's context; lifecycle practice was already active through energy-consumption simulation and traceability planning; and AI/federated-learning usage was limited. The to-be trajectory addresses each gap directly: turn designer-accessible simulation into routine practice with measurable agility

KPIs, close the digital thread and harden data quality so monitoring and the twin rely on trusted inputs, make the data container's role tangible as the contract for synchronised and authorised data, and revisit AI once foundations are stable.

4.3.2 Connected Logistics (VWAE) TO-BE

Pilot business processes: The to-be state builds on a year of progress in making logistics configuration updates routine, rather than episodic. Business Process 1 has moved from annual reconfiguration to monthly, with direct access to up-to-date logistics data via a new connection to Amazon Web Services; the goal is to institutionalise this cadence so configuration stays continuously aligned with actual production, locking in savings and agility month after month. The team reports outperforming targets in BP1 after discovering additional optimisation opportunities once the dedicated data team and AWS pathway were in place; in BP2, which aims to reduce specialist effort through digitisation and RPA (Automation Anywhere), the to-be objective is to finish calculations and, where needed, rebalance effort between "keeping the system current" and "automating the update work" so the KPI is reliably met; and in BP3 the to-be is to broaden optimisation beyond the core GT process, applying the same analytics and RTLS-based insights to similar assets in other processes to compound gains across the plant.

Data sharing and integration: The to-be integration fabric keeps AWS as the authoritative source for master logistics data while maturing two operational constraints learned during the pilot: first, frequency management and business justification for higher-than-daily refreshes across a multi-plant dataset, and second, disciplined extraction and retention for local RTLS so no time windows are lost. In practice this means retaining the default daily AWS refresh and preparing lightweight business cases, with concrete dashboards and decisions at stake, for minute-level updates where truly required; in parallel, the site should lock in an RTLS extraction schedule and retention policy that eliminates one-week data-loss risks, so historical analyses and KPI backfills remain intact. The hard-won connection path—from AWS, through the group's Calibra tooling, to on-premises dashboards—should be treated as a standard pattern, with early involvement from corporate IT whenever similar integrations are anticipated, to avoid another year-long ramp. The data container remains the backbone for unified access control and structured exposure of integrated data. In the to-be state, its value surfaces less as a "feature" and more as the invisible contract that allows shop-floor teams to trust that the information fueling monthly updates is consistent, authorised, and reproducible. External marketplace publication is out of scope for VWAE due to confidentiality; internally, however, the "data-as-a-product" mindset is already practiced when a new vehicle model leverages data from the platform used in other plants. The to-be direction is to codify that internal reuse within the container's policies and schemas, so platform lineage and reuse scenarios are deliberate and frictionless without compromising access boundaries.

AI models and federated learning: The to-be ambition is to turn today's "somewhat effective, accuracy-improving" status into a dependable production capability. Concretely, the site will continue exploiting RTLS streams—timestamped X/Y positions of line-feeding equipment—as the primary signal that improves model accuracy, while addressing the new class of challenges the team now emphasises: data-privacy assurance and governance for any AI toolchain. Federated learning remains a strategic option to scale training without centralising sensitive data; operationalising it to-be involves two commitments: privacy-by-design data handling and a clear statement of when federated training is justified over centralised workflows, tied to measurable improvements in accuracy or timeliness for the GT and adjacent processes.

Progress in integration and reference architecture: The to-be path formalises what worked in the pilot: partners map business processes to the RE4DY reference architecture, co-develop first implementations across integration and digital-continuity layers (data connection profiles, data container, simulations, federated learning), and then VWAE deploys and operates them internally. Going forward, the site will capture this mapping explicitly in its deliverables and technical playbooks so the pattern is portable and repeatable, reducing dependency on specific individuals and speeding future deployments.

Comparison with initial AS-IS: The original AS-IS placed operational-technical maturity at an initial level and supply chain at managed; the to-be targets were integration for both operations and supply chain, with other performance pillars out of scope. The interview shows those to-be directions are now concrete: direct AWS connectivity exists, monthly updates are standardising, shop-floor integration is in place, and RTLS is being harnessed for predictive positioning insights. What still separates AS-IS from the desired to-be is less technology than capacity and governance: specialist availability to sustain simulation and analytics at pace, privacy policies for AI workloads, and procedural fixes for data frequency and retention.

Next steps and recommendations. In the immediate term, complete the full deployment of the automated GT process, then capture operator and logistics-provider feedback to fine-tune configurations and lock in KPI gains. Keep daily AWS refresh as the default and request higher-frequency windows only with concrete use-case justification; stabilise RTLS extraction and retention so no analysis windows are missed. Maintain and grow the two-person data capability now in place, and resolve the long-standing simulation staffing issue by aligning with the group's central simulation team or by establishing a cross-department shared service that guarantees full utilisation; a single, plant-only role remains hard to justify. For AI, continue the RTLS-driven accuracy push while formalising privacy controls for any tool that ingests sensitive data. Finally, whenever corporate-level integrations are anticipated, bring headquarters IT and external providers into the loop early with a clear project narrative and urgency, so enabling tools like Calibra and their connectors are ready on time.

4.3.3 KPIs Interview Questions

This sub-section presents the results of the interview oriented towards operational KPIs. During the interview a set of questions were set in order to gather evidence-based view of KPI performance across the RE4DY pilots and is designed to complement the KPI definitions and baselines established in D4.2. By capturing both quantitative results and their operational context, it enables Task 4.4 to assess maturity and progress within the Performance pillar of the 6Ps framework and to generalise impact beyond single sites. The gathered responses will provide RE4DY's end-phase evaluation, guide lessons learned for future deployments, and support the handover of sustainable, data-driven practices after project close.

Table 8. KPI Interview Questions

Performance Overview & KPI Progress

• Which KPIs from D4.2 have improved since M24, and by how much? (E.g. percentage increase in yield, efficiency, uptime.) • Are there any KPIs that have not met expected targets? What factors contributed to this?
Operational Insights • What operational changes or process improvements have impacted KPIs during the last 12 months of the pilot? • Can you highlight any incidents or disruptions that temporarily affected performance metrics?
Data Collection & Accuracy • How reliable and timely has the data capture process been? Have there been any data gaps or quality issues? • Which monitoring tools or systems provided the most valuable data for KPI monitoring?
Operators' Feedback • What insights did you gather from operators (via surveys or interviews) that influenced KPI outcomes? • Engagement with operators: how did their feedback shape operational adjustments?
Challenges & Mitigation • What key challenges have you encountered since M24, and how have you addressed them? • What lessons learned would you highlight to improve process operations for future pilots?
Next Steps & Recommendations • Based on current KPI performance, what are your priorities going forward? • Are there any support actions (resources, training, tools) required from the consortium to maintain or further improve performance?

The "Performance Overview & KPI Progress" section asks which KPIs improved since M24 and by how much, and which fell short with contributing factors. "Operational Insights" documents process changes in the last 12 months and any incidents that affected metrics. "Data Collection & Accuracy" records the reliability and timeliness of capture, known gaps or quality issues, and the tools or systems that proved most valuable. "Operators' Feedback" captures insights from surveys or interviews and how they shaped operational adjustments. "Challenges & Mitigation" highlights key obstacles since M24, how they were addressed, and lessons for future pilots. "Next Steps & Recommendations" identifies priorities going forward and any support the consortium should provide to maintain or improve performance.

4.3.4 KPIs Interview with AVL

The interview with AVL representatives was aimed at understanding the operational outcomes from deploying digital-twin-enabled production systems in electric battery manufacturing. Focused on agility, energy efficiency, and rapid adaptation to product changes, this discussion seeks to quantify improvements in time-to-adapt metrics, energy consumption reductions, and process decision autonomy. Insights gathered here will enrich the benchmarking analysis for Deliverable D4.3 and illustrate how RE4DY-supported tools contributed to operational resilience in advanced manufacturing.

Performance Overview & KPI Progress

The strongest reported improvement is agility in the planning and early production-readiness phases. Making the production-simulation capability available earlier and directly to design has shortened iteration cycles, helped designers foresee manufacturability issues sooner, and generally sped up process planning. This matters at AVL because much of the work is prototype production, with many different product designs to handle; the digital-twin support improves understanding of how to produce and reduces time to adapt, even if conditions are not yet "excellent." By contrast, AVL does not expect a clear improvement in customization beyond what follows indirectly from better agility, and they explicitly state that unplanned-downtime reduction did not really improve. No quantitative uplifts were provided in the interview; the assessment is qualitative.

Operational Insights

The main operational change affecting KPIs in the last 12 months was integrating production simulation earlier in the design workflow so designers themselves can quickly see where problems could arise and iterate faster with planning. This has concentrated and shortened iteration steps and is the reason agility improved. AVL did not recall specific incidents or disruptions during the call, but committed to check internally if needed.

Data Collection & Accuracy

Data capture is in place but not yet robust end-to-end. AVL reports missing data and occasional wrong values, i.e., reliability and quality issues that affect monitoring. For collection, they rely "basically" on a cloud service; for monitoring, they have established Power BI dashboards. Those dashboards source data from an in-house server rather than a purely external warehouse. This combination supports visibility but the quality gaps limit KPI confidence and trend analysis. Two digital-service threads are highlighted. First, the digital twin that supports resilience-oriented production simulation, which accelerates planning by allowing earlier feasibility checks and shorter design-to-plan cycles. Second, a simulation tool for energy consumption that helps study how to reduce energy use and, importantly, helps track how much energy is used to produce each battery pack—valuable input for the emerging "battery passport" requirements. Together these services improve planning speed and transparency on energy, even if other KPI domains show less movement.

Operators' Feedback

Initial shop-floor feedback emphasized usability. As with any new program inserted into a workflow, there was some confusion at first; users judged the tool could be more user-friendly. This suggests a design focus on simplifying interactions and clarifying task flows would help adoption and thereby support KPI outcomes downstream. AVL recognizes that further work on usability is needed; concrete adjustments were not enumerated in the call.

Challenges and Mitigation

The most salient challenge is data-related. There are gaps, missing values, and, at times, incorrect entries; it can even be difficult to assemble a good reference dataset. More broadly, AVL recognizes that production data today is used mainly for traceability rather than to learn deeply about process behaviour, so analytical leverage remains underexploited. In parallel, early uncertainty over what to share and why delayed data-sharing value, and limited use of AI/federated learning means there is not yet a body of technical "lessons" in that area at AVL. AVL did not list specific mitigations beyond the in-progress steps described above, but the thrust is clear: raise data completeness and correctness, and expand production-data use beyond traceability.

Lessons Learned

AVL principal lesson is to use production data better than they do now, moving beyond pure traceability to process learning and improvement. They also stress that data gaps are a "pretty big problem," with difficulty even in finding solid reference datasets at times. That points to the need for a more deliberate data-quality and reference-dataset program early in a pilot, especially where KPIs depend on reliable monitoring and modelling.

Next Steps and Recommendations

Looking forward, the priority for AVL remains agility, since they serve many different customers and must adapt quickly from design to production. They also expect to benefit from RE4DY training materials; AVL had only just discovered the set but believes several items could be useful, calling out supply-chain topics as particularly relevant given the battery-passport reporting obligations. The energy-consumption simulation will be useful to support that passport by transparently tracking the energy used to produce each pack. On support needs, they did not request ongoing consortium resources; instead, ad-hoc help from the technology partner may be sought as needed. In sum, near-term recommendations are to harden data capture and quality, streamline the user experience for the production-simulation tool to boost adoption, continue integrating energy-tracking into planning workflows, and use the RE4DY training material where it aligns with supply-chain and battery-passport priorities.

4.3.5 KPIs Interview with VWAE

This interview with the VWAE pilot team focused on the implementation and impact of digital continuity and logistics resilience at Volkswagen Autoeuropa. We explore how data-led logistics planning, adaptive GT-process configuration, real-time RTLS tracking, and e-paper shop-floor tools have influenced key performance indicators such as cost reduction, change-over time improvements, and process stability. This conversation builds on the mid-term KPIs outlined in D4.2 by capturing end-of-project values and strategic reflections from the Volkswagen use-case.

Performance Overview & KPI Progress

The overall progress is described as good. For Business Process 1, the team reports achieving and even surpassing its expected KPI target after establishing a direct connection to Amazon Web Services to access up-to-date logistics data, a first for the plant that materially improved the timeliness and scope of information available for planning. The interviewee credits a dedicated team working on this business process with discovering additional savings and improvements beyond initial expectations. For Business Process 2, which aims to reduce effort from logistics specialists by digitising and automating steps, the result is still uncertain at the time of the interview; a robotic process automation approach using Automation Anywhere was put in place to relieve manual updates, but the interviewee remains hesitant about whether the KPI target will be fully met once final calculations are done. For Business Process 3, the team is confident it will at least meet and possibly surpass the target by applying the real-time location system data not only to the main "GT" line-feeding process addressed in all three business processes, but also to similar assets in other processes, thereby broadening the optimisation impact. A cross-cutting effect on KPI performance comes from the move to frequent configuration updates of the "GT" process: the plant shifted from updating roughly once a year to updating monthly, which keeps the system in line with current production and makes savings more continuous.

Operational Insights

The most consequential operational change in the last 12 months was the successful integration of the plant's logistics dashboards directly with AWS, rather than via legacy systems or intermediate consolidation layers. This new pathway was built under RE4DY and is considered a novelty for logistics within the organisation. In parallel, the plant improved staffing by assigning two people dedicated to data work, which enabled the creation of additional dashboards and strengthened internal capability. A temporary but significant disruption was the integration timeline itself: because multiple IT departments and vendors had to be involved and because the corporate tool to move data from AWS to on-premises was not yet ready when first requested, the end-to-end connection took almost one year to complete.

Data Collection & Accuracy

For the AWS-sourced logistics data, collection is characterised as reliable, with the main limitation being refresh frequency. By default, the plant receives a daily update; while minute-level refresh is technically possible, the corporate owners require strong justification due to the resource cost of higher-frequency access across a very large multi-plant dataset. For the local real-time location system, the plant initially faced architectural and retention challenges because this is a locally operated database unique within the group and subject to local rules. The retention period at one point was only about a week, so missed extractions created gaps; the team learned to schedule extraction carefully and reports having worked through the issue. Across both streams, the data sources contributing the most to KPI monitoring are master data from the corporate AWS and the locally generated RTLS data from line-feeding assets.

Operators' Feedback

Full deployment of the automated "GT" process on the shop floor is still approaching, so the plant does not yet have direct operator feedback to report. The team expects to gather it once the deployment is live and anticipates that both internal colleagues and the logistics service provider will suggest adjustments to further improve the process and its KPIs.

Challenges and Mitigation

The biggest challenge was the AWS connection itself, which took close to a year and required coordination across local IT, corporate IT, colleagues in other plants, and Amazon. The lesson drawn is to bring corporate stakeholders into the loop as early as possible, presenting concrete project context and urgency so that enabling tools and connectors can be readied in time; generic requests without detailed context did not trigger sufficient priority. On the data side, refresh-frequency constraints and local RTLS retention initially limited timeliness and continuity, but the plant worked around these through justification processes for higher-frequency access where needed and through more disciplined extraction schedules.

Next Steps and Recommendations

The immediate priority is to complete the rollout of the automated GT process with monthly updates now in place, then collect and act on shop-floor and provider feedback to refine configurations and sustain KPI gains. The team will continue operating with daily AWS refresh by default and will pursue higher-frequency updates only where the business case is clear. Internally, the plant intends to keep expanding data-driven dashboards now that two dedicated data specialists are in place. For simulation, the recommendation is organisational rather than technical: align with the central simulation capability at group level or establish a cross-departmental arrangement that can keep a specialist fully utilised; the interviewee does not see a way to justify an isolated full-time plant role under current workload patterns. The team does not request ongoing resources from RE4DY to maintain performance after project close.

5 Conclusion

D4.3 demonstrates that both VWAE and AVL moved beyond proofs of concept to deployable, operations-aligned solutions that connect simulation, data integration, and shop-floor practices under the RE4DY reference architecture. The evidence assembled here, architectural descriptions, industrial trials, KPI monitoring, and end-phase interviews, shows measurable progress on process digitalisation and decision support, while also surfacing the practical dependencies that determine portability and scale.

At VWAE, a coherent, closed loop now links planning automation (GT-Process), a scenario-simulation twin (Twiserion), e-paper-based shop-floor updates, and targeted RTLS streams that validate and refine logistics flows. This ensemble has been exercised through structured on-site trials for autonomous planning, shop-floor implementation, and resource optimisation, with iterative feedback from planners and line-feeding teams. The result is a repeatable pattern that reduces planning effort, accelerates configuration updates, and improves transparency of asset usage, supported by a unified reporting layer that combines GT-Process, RTLS, and shop-floor signals. The most consequential lesson is organisational: early involvement of corporate IT and phased roll-outs were as critical as any individual technology in turning an annual reconfiguration cycle into a monthly, data-driven routine. Remaining constraints are primarily capacity- and governance-related (e.g., AWS connectivity lead-times, RTLS retention and coverage), not feasibility, and are already being mitigated through standardised connectors, disciplined extraction schedules, and targeted sensor placement.

At AVL, the final architecture centres on a Visual Components–based digital twin of the Battery Innovation Center, extended with RE4DY-aligned plugins for CAD/3DXML-driven auto-setup, manufacturability "resiliency" checks, SQL-backed event synchronisation, robotic-energy estimation, and human-resource simulation. Trials indicate tangible gains: earlier and more accurate planning before physical prototyping, faster manufacturability iteration, improved energy visibility for forthcoming battery-passport reporting, and a reduction in reject rates across comparable periods. As with VWAE, the enablers were robust data plumbing and disciplined change management; the limiting factors were long-run statistics (given prototype variability) and the effort to model new assets with sufficient fidelity. The work nonetheless establishes a durable backbone for bringing simulation upstream into design and for validating plans against real shop-floor signals.

KPI assessment in D4.3 follows the 6Ps Performance pillar: rather than claiming improvements solely on outcome values, it evaluates how indicators are defined, measured, governed and made traceable. Applied through structured surveys and interviews, this lens confirms that both pilots strengthened digital-continuity foundations and measurement practices, VWAE around logistics cost efficiency, planning agility and implementation speed; AVL around planning accuracy, manufacturability iteration time, and energy/quality visibility, while also acknowledging where targets were hard to verify due to data windows, scope, or prototype constraints. This approach makes results comparable with D5.3 and supports generalisation beyond single sites.

Across pilots, four cross-cutting conclusions emerge. First, simulation only becomes operationally valuable when fed by governed, synchronised data and when its outputs are embedded in day-to-day workflows; both sites show this is achievable with pragmatic rollouts and clear ownership. Second, change management and skills availability are the primary bottlenecks once the basic stack is in place; success hinged on early stakeholder engagement and on dedicating the right profiles to sustain monthly updates, RTLS analytics, and twin interpretation. Third, standardised connectors, documented data lineages, and component-to-layer mappings are prerequisites for portability, VWAE's AWS pathway and AVL's SQL/twin synchronisation illustrate the point and should be codified as patterns. Fourth, AI and federated learning remain optional accelerants in these contexts; both pilots correctly prioritised trustworthy data, simulation, and governance first, setting a cleaner runway for any model-based scaling later.

The results presented directly support RE4DY's objectives by demonstrating how connected, digitally enabled factories can be achieved. The pilots show tangible progress in establishing interoperable digital twins, integrating heterogeneous data sources, and embedding simulation outputs into operational workflows, all of which advance the project's goals of data-driven decision-making, enhanced production efficiency, and scalable, cross-site adoption of smart manufacturing solutions. By validating both technological components and human-centred deployment strategies, the pilots provide a concrete pathway for other industrial sites to implement RE4DY concepts effectively.

In closing, D4.3 provides an auditable, practice-centred account of how VWAE and AVL converted RE4DY concepts into plant-ready capabilities. The combination of twin-centred planning, harmonised data flows, and user-oriented roll-out produced measurable efficiency and agility gains and clarified the operational guardrails for scale. Immediate post-project priorities are to maintain the monthly logistics-configuration cadence and RTLS discipline at VWAE, to continue hardening AVL's twin/data synchronisation while broadening validation datasets, and across both, to formalise patterns for data governance, interfaces, and role ownership so that replication across lines and sites is faster, safer, and more predictable.

6 Annex

1st Iteration of analysis – (AS-IS situation)

Dear Partners,

The 6Ps methodology is a comprehensive tool designed to aid enterprises in their digital transformation journey by thoroughly analyzing six key dimensions: product, process, platform, people, partnership, and performance. This methodology emphasizes the importance of enhancing both technical and socio-business aspects to achieve successful digital transformation.

For our survey, we are focusing solely on the **Performance** dimension. This pilot experiment will compare the initial and final performance levels to measure the impact on the company's production process.

The survey includes a series of multiple-choice questions specifically tailored to assess the Performance dimension.

As the project approaches its conclusion, participants will need to indicate their initial status before the project (**As-Is**) and the actual situation (**To-Be**).

The full compilation of the survey will take you approximately 15 minutes overall, but you're allowed to save your partial compilation and reprehend it after a while.

Q43. The RE4DY project team will process the results of the survey only in order to draft a report. Your privacy, personal and company data protection will be guaranteed in conformity with the European Regulation (EU) 2016/679. Your data will be processed in a separate database from the results of the survey in order to guarantee the anonymity of the survey and will not link your data with other databases. For more information regarding the processing of your data, you can visit here.

- [x] Agree

6.1 AVL 1st Iteration of analysis – (AS-IS situation)

Martin

Q35. LAST NAME

Weinzerl

Q33. E-MAIL

martin.weinzerl@avl.com

Q34. COMPANY

AVL List GmbH

Q49.

PERFORMANCE

Performance dimension aims at investigating what is the AS-IS status before the project and the desired level of control over your company's processes and activities.

- (x) COMPILE THE PERFORMANCE SURVEY
- ( ) GO TO THE Conclusion

Q83.

Q31.

OPERATIONAL/ TECHNICAL

What approach does your company adopt for measuring operational performances (e.g. OEE)?

1. INITIAL: Operational performance is often not measured or understood
2. MANAGED: Descriptive Performance - Measurement and analysis of business KPIs are largely retrospective
3. DEFINED: Diagnostic Performance - Measurement of KPIs is clear. Attempt to understand the causes that affects events and behaviours
4. INTEGRATED: Predictive Performance - Measurement of KPIs is prospective. Statistical models are used to forecast and to understand the KPIs predictions
5. EXPLOITED: Prescriptive Performance – future-oriented. Optimization and simulation to find the best course of action and operational KPIs measurement. AI/ML models are used to forecast and to understand the KPIs predictions

	AS-IS	TO-BE
INITIAL	◉	○
MANAGED	○	○
DEFINED	○	○
INTEGRATED	○	○
EXPLOITED	○	◉
Not Applicable	○	○

Q32.

ECONOMIC

What approach does your company adopt for measuring economic performances (e.g. ROI)?

1. INITIAL: Economic performance is often not measured or understood
2. MANAGED: Descriptive – Measurement of economic KPIs is largely retrospective
3. DEFINED: Diagnostic - Measurement of economic KPIs is clear. Attempt to understand the causes of events and behaviours
4. INTEGRATED: Predictive - Measurement of economic KPIs is prospective. Statistical models and forecasts techniques to understand the KPIs predictions
5. EXPLOITED: Prescriptive – future-oriented. An AI decision-making support system boosting optimization exploits simulation and allows to find the best course of actions and operational KPIs measurement

	AS-IS	TO-BE
INITIAL	○	○
MANAGED	○	○

DEFINED	●	○
INTEGRATED	○	○
EXPLOITED	○	●
Not Applicable	○	○

Q33.
ENVIRONMENTAL
What approach does your company adopt for measuring environmental performances (e.g. water consumption per product, energy optimisation) ?

1. INITIAL: Environmental performance is often not measured or understood
2. MANAGED: Descriptive – Measurement of environmental KPIs is largely retrospective
3. DEFINED: Diagnostic - Measurement of environmental KPIs is clear. We attempt to understand the causes of events and behaviours
4. INTEGRATED: Predictive - Measurement of environmental KPIs is prospective. AI and/or statistical models are used to forecast environmental performances
5. EXPLOITED: Prescriptive – future-oriented. An AI decision-making support system boosting optimization exploits simulation and allows to find the best course of action and environmental KPIs measurement

	AS-IS	TO-BE
INITIAL	○	○
MANAGED	○	○
DEFINED	●	○
INTEGRATED	○	○
EXPLOITED	○	●
Not Applicable	○	○

Q34.
SOCIAL
What approach does your company adopt for measuring social performances (e.g. welfare for employees)?

1. INITIAL: Social performance is often not measured or understood
2. MANAGED: Descriptive - Measurement of social KPIs is largely retrospective
3. DEFINED: Diagnostic - Measurement of social KPIs is clear. Attempt to understand the causes of events and behaviours
4. INTEGRATED: Predictive - Measurement of social KPIs is prospective. AI and/or statistical models are used to forecast social performances
5. EXPLOITED: Prescriptive – future-oriented. An AI decision-making support system boosting optimization exploits simulation and allows to find the best course of action and environmental KPIs measurement

	AS-IS	TO-BE
INITIAL	○	○
MANAGED	○	○
DEFINED	●	○
INTEGRATED	○	○
EXPLOITED	○	●
Not Applicable	○	○

Q35.

PRODUCT-SERVICE LIFECYCLE

Which dimensions of analysis are taken into account in the assessment of lifecycle of the products/services offered to the customers?

1. INITIAL: No product life cycle assessment
2. MANAGED: A few life-cycle aspects are included in some KPIs, but occasionally
3. DEFINED: Life Cycle Costing (LCC) towards recycling, re-use, de- re-manufacturing KPIs
4. INTEGRATED: Life Cycle Costing + Environmental LCA towards Circular Economy
5. EXPLOITED: Life Cycle Costing + Environmental LCA + Social LCA towards Sustainability and Green Deal

	AS-IS	TO-BE
INITIAL	○	○
MANAGED	○	○
DEFINED	○	○
INTEGRATED	○	○
EXPLOITED	●	●
Not Applicable	○	○

Q36.

SUPPLY CHAIN

Which dimensions of analysis are taken into account for the overall evaluation of your company's supply chain?

1. INITIAL: The Supply Chain performances are lowly monitored/measured.
2. MANAGED: We measure only the most important physical performance of suppliers (e.g. punctuality, quality, operational flexibility)
3. DEFINED: We measure physical and economical performances (purchase price, non-quality costs, delivery delays, lack of flexibility, etc.).
4. INTEGRATED: We measure physical and economical performances, and sustainability indexes.
5. EXPLOITED: We measure physical and economical performances, sustainability indexes and cross-company value creation.

	AS-IS	TO-BE
INITIAL	○	○
MANAGED	●	○
DEFINED	○	○
INTEGRATED	○	●
EXPLOITED	○	○
Not Applicable	○	○

Q14.

Pilot business processes

How would you rate the progress in achieving objectives for process planning and preparation?

	Rate
Excellent	○

Good	◉
Average	○
Poor	○
Insufficient	○

Q71. What key milestones have been reached in process planning and preparation? (Please list any significant achievements)

> Defining main process within company first process flow tested

Q17. What challenges or bottlenecks have you encountered in implementing process planning and preparation? (Please specify)

> unforeseeable difficulties in integrating into existing IT infrastructure and process landscape

Q15.
<u>**Data Sharing and Integration**</u>
How would you rate the progress in connecting data sources and synchronizing data at your site on the dedicated Data Container?

	Rate
Excellent Progress	○
Good Progress	○
Average Progress	◉
Poor Progress	○

Q18.

What challenges have you faced in the data sharing and integration process?

	Challenges
Difficulty connecting data sources	○
Issues with data synchronization	○
Concerns about data security and privacy	○

Q22.
AI Models and Federated Learning
How would you rate the progress in leveraging on Federated Learning at your site?

	Rate
Excellent progress	○
Good progress	○
Average progress	◉
Poor progress	○
Insufficient progress	○

Q23.

How effective has the Federated Learning approach been in enhancing AI models?

	Rate
Very effective	○
Somewhat effective	○
Neutral	◉
Not very effective	○
Not at all effective	○

Q24.

What benefits have you observed from implementing Federated Learning? (Select all that apply)

	Benefits
Improved model accuracy	☑
Enhanced data privacy	☐
Reduced data transfer costs	☐
No significant benefits observed	☐

Q25.

What challenges have you faced in implementing Federated Learning? (Select all that apply)

	Challenges

Technical difficulties in deployment	☐
Data privacy concerns	☐
Lack of expertise	☐
Integration with existing systems	☐
No challenges faced	☑

Q26. Are there any other comments or feedback you would like to provide regarding AI models and Federated Learning in the RE4DY pilot?

Q27.

Progress in Integration

How would you rate the progress in integrating the RE4DY components and achieving the planned objectives at your pilot site?

	Rate
Excellent	○
Good	●
Average	○
Poor	○
Insufficient	○

Q28.

Which of the following key achievements have been reached at your pilot site? (Select all that apply)

	Achievements
Successful connection of data sources to the Data Container	☐
Implementation of predictive maintenance solutions	☐
Development of digital twins for tools and machines	☑
Completion of significant data synchronization tasks	☑
None of the above (please specify)	☐

Q29. None of the above (please specify)

Q30.

What are the main challenges and roadblocks you have encountered in implementing the pilot at your site? (Select all that apply)

	Challenges
Technical difficulties with data integration	☐
Insufficient resources or expertise	☐
Resistance to change from staff	☐
Issues with data quality or availability	☐
No significant challenges faced	☑

Q31. Are there any other comments or feedback you would like to provide regarding the integration of RE4DY components at your pilot site?

Q74.

6.2 VWAE 1st Iteration of analysis – (AS-IS situation)

Diogo

Q35. LAST NAME

Graça

Q33. E-MAIL

diogo.graca@volkswagen.pt

Q34. COMPANY

Volkswagen Autoeuropa

Q49.

Performance dimension aims at investigating what is the AS-IS status before the project and the desired level of control over your company's processes and activities.

- [x] COMPILE THE PERFORMANCE SURVEY
- [ ] GO TO THE Conclusion

Q83.

Q31.

OPERATIONAL/ TECHNICAL

What approach does your company adopt for measuring operational performances (e.g. OEE)?

1. INITIAL: Operational performance is often not measured or understood
2. MANAGED: Descriptive Performance - Measurement and analysis of business KPIs are largely retrospective
3. DEFINED: Diagnostic Performance - Measurement of KPIs is clear. Attempt to understand the causes that affects events and behaviours
4. INTEGRATED: Predictive Performance - Measurement of KPIs is prospective. Statistical models are used to forecast and to understand the KPIs predictions
5. EXPLOITED: Prescriptive Performance – future-oriented. Optimization and simulation to find the best course of action and operational KPIs measurement. AI/ML models are used to forecast and to understand the KPIs predictions

	AS-IS	TO-BE
INITIAL	●	○
MANAGED	○	○
DEFINED	○	○
INTEGRATED	○	●
EXPLOITED	○	○
Not Applicable	○	○

Q32.

ECONOMIC

What approach does your company adopt for measuring economic performances (e.g. ROI)?

1. INITIAL: Economic performance is often not measured or understood
2. MANAGED: Descriptive – Measurement of economic KPIs is largely retrospective
3. DEFINED: Diagnostic - Measurement of economic KPIs is clear. Attempt to understand the causes of events and behaviours
4. INTEGRATED: Predictive - Measurement of economic KPIs is prospective. Statistical models and forecasts techniques to understand the KPIs predictions
5. EXPLOITED: Prescriptive – future-oriented. An AI decision-making support system boosting optimization exploits simulation and allows to find the best course of actions and operational KPIs measurement

	AS-IS	TO-BE
INITIAL	○	○
MANAGED	○	○

DEFINED	○	○
INTEGRATED	○	○
EXPLOITED	○	○
Not Applicable	◉	◉

Q33.
ENVIRONMENTAL
What approach does your company adopt for measuring environmental performances (e.g. water consumption per product, energy optimisation) ?

1. INITIAL: Environmental performance is often not measured or understood
2. MANAGED: Descriptive – Measurement of environmental KPIs is largely retrospective
3. DEFINED: Diagnostic - Measurement of environmental KPIs is clear. We attempt to understand the causes of events and behaviours
4. INTEGRATED: Predictive - Measurement of environmental KPIs is prospective. AI and/or statistical models are used to forecast environmental performances
5. EXPLOITED: Prescriptive – future-oriented. An AI decision-making support system boosting optimization exploits simulation and allows to find the best course of action and environmental KPIs measurement

	AS-IS	TO-BE
INITIAL	○	○
MANAGED	○	○
DEFINED	○	○
INTEGRATED	○	○
EXPLOITED	○	○
Not Applicable	◉	◉

Q34.
SOCIAL
What approach does your company adopt for measuring social performances (e.g. welfare for employees)?

1. INITIAL: Social performance is often not measured or understood
2. MANAGED: Descriptive - Measurement of social KPIs is largely retrospective
3. DEFINED: Diagnostic - Measurement of social KPIs is clear. Attempt to understand the causes of events and behaviours
4. INTEGRATED: Predictive - Measurement of social KPIs is prospective. AI and/or statistical models are used to forecast social performances
5. EXPLOITED: Prescriptive – future-oriented. An AI decision-making support system boosting optimization exploits simulation and allows to find the best course of action and environmental KPIs measurement

	AS-IS	TO-BE
INITIAL	○	○
MANAGED	○	○
DEFINED	○	○
INTEGRATED	○	○
EXPLOITED	○	○
Not Applicable	◉	◉

Q35.

PRODUCT-SERVICE LIFECYCLE

Which dimensions of analysis are taken into account in the assessment of lifecycle of the products/services offered to the customers?

1. INITIAL: No product life cycle assessment
2. MANAGED: A few life-cycle aspects are included in some KPIs, but occasionally
3. DEFINED: Life Cycle Costing (LCC) towards recycling, re-use, de- re-manufacturing KPIs
4. INTEGRATED: Life Cycle Costing + Environmental LCA towards Circular Economy
5. EXPLOITED: Life Cycle Costing + Environmental LCA + Social LCA towards Sustainability and Green Deal

	AS-IS	TO-BE
INITIAL	○	○
MANAGED	○	○
DEFINED	○	○
INTEGRATED	○	○
EXPLOITED	○	○
Not Applicable	◉	◉

Q36.

SUPPLY CHAIN

Which dimensions of analysis are taken into account for the overall evaluation of your company's supply chain?

1. INITIAL: The Supply Chain performances are lowly monitored/measured.
2. MANAGED: We measure only the most important physical performance of suppliers (e.g. punctuality, quality, operational flexibility)
3. DEFINED: We measure physical and economical performances (purchase price, non-quality costs, delivery delays, lack of flexibility, etc.).
4. INTEGRATED: We measure physical and economical performances, and sustainability indexes.
5. EXPLOITED: We measure physical and economical performances, sustainability indexes and cross-company value creation.

	AS-IS	TO-BE
INITIAL	○	○
MANAGED	◉	○
DEFINED	○	○
INTEGRATED	○	◉
EXPLOITED	○	○
Not Applicable	○	○

Q14.

Pilot business processes

How would you rate the progress in achieving objectives for process planning and preparation?

	Rate
Excellent	○

Good	●
Average	○
Poor	○
Insufficient	○

Q71. What key milestones have been reached in process planning and preparation? (Please list any significant achievements)

> The key milestones achieved include the successful integration of data systems to the shop floor, enhancing adaptability and flexibility. In previous EU projects, we managed to consolidate various data silos, and we are now progressing towards a scenario where future logistics configurations are accessible directly to the shop floor. This is accomplished through the generation of data analytics and simulations. The necessary infrastructure is already deployed on the shop floor, ensuring that the operational teams have real-time access to the information needed to implement the new configurations in the near future.

Q17. What challenges or bottlenecks have you encountered in implementing process planning and preparation? (Please specify)

> e have encountered challenges related to hardware deployment and software development, which, while manageable, are not the primary obstacles. The most significant challenge lies in identifying and securing the right human resources with the necessary skills to disseminate and implement simulation technology within the industry. As this technology is relatively new to our company, maintaining momentum for this initiative becomes difficult without the adequate personnel to ensure its sustainability over time.

Q15.

Data Sharing and Integration

How would you rate the progress in connecting data sources and synchronizing data at your site on the dedicated Data Container?

	Rate
Excellent Progress	○
Good Progress	●
Average Progress	○
Poor Progress	○

Q18.

What challenges have you faced in the data sharing and integration process?

	Challenges
Difficulty connecting data sources	○
Issues with data synchronization	○
Concerns about data security and privacy	○

Lack of resources or expertise	●
Other challenges (please specify)	○

Q16. OTHER CHALLENGES

Q19.

How effective has the Data Container been in enabling data exchange and services implementation?

	Rate
Very effective	○
Somewhat effective	○
Neutral	●
Not very effective	○
Not at all effective	○

Q20.

What benefits have you seen from using the Data Container for data sharing and integration?

	Benefits
Improved data visibility and transparency	○
Ability to implement new digital services	○
Enhanced data-driven decision making	●
Cost savings from streamlined data processes	○
Other benefits (please specify)	○

Q21. OTHER BENEFITS

Q22.

AI Models and Federated Learning

How would you rate the progress in leveraging on Federated Learning at your site?

	Rate
Excellent progress	○
Good progress	●
Average progress	○
Poor progress	○
Insufficient progress	○

Q23.

How effective has the Federated Learning approach been in enhancing AI models?

	Rate
Very effective	○
Somewhat effective	●
Neutral	○
Not very effective	○
Not at all effective	○

Q24.

What benefits have you observed from implementing Federated Learning? (Select all that apply)

	Benefits
Improved model accuracy	☑
Enhanced data privacy	☐
Reduced data transfer costs	☐
No significant benefits observed	☐

Q25.

What challenges have you faced in implementing Federated Learning? (Select all that apply)

	Challenges

Technical difficulties in deployment	☐
Data privacy concerns	☐
Lack of expertise	☑
Integration with existing systems	☐
No challenges faced	☐

Q26. Are there any other comments or feedback you would like to provide regarding AI models and Federated Learning in the RE4DY pilot?

Q27.
Progress in Integration
How would you rate the progress in integrating the RE4DY components and achieving the planned objectives at your pilot site?

	Rate
Excellent	◯
Good	◉
Average	◯
Poor	◯
Insufficient	◯

Q28.

Which of the following key achievements have been reached at your pilot site? (Select all that apply)

	Achievements
Successful connection of data sources to the Data Container	☑
Implementation of predictive maintenance solutions	☐
Development of digital twins for tools and machines	☑
Completion of significant data synchronization tasks	☐
None of the above (please specify)	☐

Q29. None of the above (please specify)

Q30.

What are the main challenges and roadblocks you have encountered in implementing the pilot at your site? (Select all that apply)

	Challenges
Technical difficulties with data integration	☐
Insufficient resources or expertise	☑
Resistance to change from staff	☐
Issues with data quality or availability	☐
No significant challenges faced	☐

Q31. Are there any other comments or feedback you would like to provide regarding the integration of RE4DY components at your pilot site?

Q74.