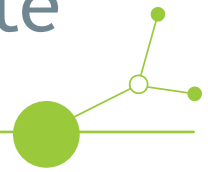


Deliverable D3.1.2 - Report on development of joint digital solutions to enable and accelerate circularity in public transport



Solutions:

1. Modules for predictive maintenance of infrastructure and rolling stock
2. Circular business planning tool for electrified public transport fleets and infrastructure

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Solutions O3.2 - Modules for predictive maintenance of infrastructure and rolling stock and O3.4 Circular business planning tool for electrified public transport fleets and infrastructure

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1. Executive summary

The CE4CE project has developed and validated a set of complementary digital solutions to support the transition towards more circular, resource-efficient public transport systems. These solutions address key challenges faced by transport operators across Europe, including fragmented data environments, reactive maintenance practices, and the lack of structured, KPI-based planning approaches for circular economy implementation.

Rather than delivering a single standalone tool, CE4CE provides a **modular and integrated solution framework** that combines strategic planning, advanced analytics, and operational implementation. The overarching objective is to enable public transport operators and authorities to move from isolated initiatives towards a **systematic, data-driven and circular management approach** covering infrastructure, rolling stock and energy systems.

Within CE4CE, three complementary pilot actions were developed, tested and evaluated as follows:

- A set of **predictive maintenance and energy simulation modules (ATB Mobility, Bergamo, Italy)**, combining real-time monitoring with digital-twin-based analysis to optimise infrastructure performance and energy use;
- An **operational implementation and integration model for predictive maintenance (LVB - Leipzig Public Transport Company, Leipzig, Germany)**, demonstrating how data acquisition, analytics (including AI-based detection) and technical components can be embedded into organisational processes, maintenance workflows and asset management systems under real operational conditions.
- A **circular business planning and KPI framework (PKA - Bus Operator in Gdynia, Poland)**, supporting structured, comparable and evidence-based decision-making for electrified transport systems.

These pilot activities go beyond technical testing, they also validate organisational setups, methodological approaches and economic feasibility. They provide valuable insights into real-world challenges, barriers and success factors, and allow the derivation of practical and transferable solutions. They were intentionally designed to address different layers of the public transport value chain, from strategic planning to technical analysis and operational implementation. This approach enables a comprehensive understanding of how circular economy principles can be effectively embedded in practice.

The joint CE4CE solution (deliverable D3.1.2) is built on the above-mentioned complementary pilot actions. Together, these solutions form layered architecture, where:

- KPI-based planning defines objectives and targets,
- data analytics and simulations generate evidence,
- and operational processes ensure effective implementation.



This overarching document consolidates the results of the three pilots into a **unified solution framework**, providing a high-level description of the joint architecture, governance model, and implementation logic. While detailed methodologies, technical specifications and use cases are documented in the annexed pilot solutions, this document focuses on the **integration, transferability and scalability** of the CE4CE approach.

The CE4CE solution has been validated through real-world pilot actions in Leipzig, Bergamo and Gdynia, demonstrating its applicability across different operational, technical and organisational contexts. The results show that a combination of predictive maintenance, simulation-based planning and KPI-driven governance can significantly contribute to:

- extending the lifetime of infrastructure and rolling stock,
- reducing material consumption and waste,
- improving energy efficiency and the reuse of recuperated energy,
- increasing operational reliability and reducing unplanned disruptions,
- strengthening data-driven decision-making and long-term investment planning.

A key added value of the CE4CE approach lies in its **modularity and transferability**. Public transport operators can adopt individual components depending on their maturity level and gradually expand towards a fully integrated solution. This enables flexible deployment across diverse institutional and technical environments while maintaining a common methodological foundation.

By providing both a **coherent system architecture** and validated pilot implementations, CE4CE delivers a practical and scalable contribution to the implementation of circular economy principles in public transport at European level.

2. Project context

The CE4CE project (“Circular Economy for Central Europe”) aims to strengthen circular economy system thinking in public transport and to develop practical solutions for transport operators and public authorities in Central Europe. The focus lies on improving resource efficiency along the entire lifecycle of infrastructure and rolling stock, reducing waste, and creating value through extended asset use.

Public transport systems are generally well positioned to implement circular economy principles, but they also face significant structural challenges. These include ageing infrastructure, increasing requirements for reliability and service quality, growing investment needs, and rising regulatory pressure related to climate protection and resource efficiency. At the same time, the data required for systematic assessment of asset condition, energy flows and lifecycle performance is often fragmented or not fully accessible.

Against this background, CE4CE addresses the gap between strategic circular economy ambitions and their practical implementation in daily transport operations. The objective is to develop approaches that are not only conceptually sound but also tested and validated under real operational conditions.

The conceptual framework laying the basis for all project activities consisted of the **Circularity Compass**. The tool has provided an important conceptual and practical foundation for the CE4CE project solutions by translating circular economy principles into a public transport life-cycle logic. Its structure covers the main stages and assets of public transport systems, including planning, procurement, operations, maintenance and end-of-life, and frames circular action through the **Avoid-Extend-Transform-Enable** model. It also uses



key circularity principles such as redesign, reduce, reuse, repair, retrofit and recycle to help public transport authorities and operators assess where they stand, identify gaps and recognise realistic opportunities for action across infrastructure, vehicles, energy and governance.

This approach directly supported the development of the **modules for predictive maintenance of infrastructure and rolling stock** under output **O3.2**. By emphasising “extend” measures, durable and repairable assets, and life-cycle-based decision-making, the Compass helped frame predictive maintenance not only as a digital innovation, but as a circular economy solution. In the Leipzig and Bergamo pilots, this logic is reflected in the shift from reactive and manual maintenance towards sensor-based, data-driven and automated condition monitoring. The resulting modules support early fault detection, damage catalogues, asset assessment and forecasts, helping to reduce unnecessary routine checks, avoid major breakdowns, lower repair costs and extend the useful life of infrastructure and vehicles.

The Compass has also contributed to the **Circular business planning tool for electrified public transport fleets and infrastructure** under output **O3.4** by encouraging a broader assessment of circular value, costs and impacts across the full public transport system. In Gdynia, this is reflected in the development of a digital-twin-based tool that uses real-life data on electric buses, chargers, energy consumption, charging performance and energy flows to simulate electrification scenarios. The tool supports decisions on charging strategies, use of existing trolleybus infrastructure, charger and photovoltaic locations, electricity demand, energy costs and cost-benefit analysis. In this way, the Circularity Compass helped orient the tool towards resource-saving, life-cycle-based and transferable business planning for electrified public transport systems.

Moreover, the Action Plans prepared by project partners LVB, PKA and ATB acted as the main bridge between the CE4CE strategic framework, and the practical solution development described in deliverable D3.1.2 for outputs O3.2 and O3.4. The **LVB Action Plan** (Output O2.5) on optimising infrastructure delivery through minimally invasive maintenance in Leipzig provided the operational basis for O3.2, helping to define how predictive maintenance modules should support condition monitoring, asset assessment, damage catalogues, standardised data interfaces and future roll-out across the network. The **PKA Action Plan for Gdynia** (output O2.6) informed O3.4 by translating circular economy principles into a concrete local case of infrastructure sharing and electrification planning. Its focus on optimising the use of fast chargers, existing trolleybus infrastructure, e-buses and related energy flows provided the practical requirements for the circular business planning tool, including simulation of electrification scenarios, energy management, cost-benefit analysis and assessment of infrastructure and fleet lifetime benefits. The **ATB Action Plan** (output O2.7) added a rolling-stock and procurement perspective, particularly through its focus on circular procurement criteria for e-buses and research into predictive maintenance of e-buses. Together, these Action Plans ensured that D3.1.2 was not developed as a generic technical description, but as a solution-oriented document grounded in real operator needs, local infrastructure conditions, stakeholder requirements and transferable circular economy use cases.

This overarching document builds on the results of the pilot actions and action plans and consolidates them into a joint solution framework. Its purpose is not to present the individual pilot solutions in isolation, but to highlight their interconnections and provide a structured basis for transfer and replication in other cities and transport organisations.

3. The objectives and scope of the solution

The overarching solution defines the methodological and architectural foundation uniting the three CE4CE pilot solutions (predictive maintenance for infrastructure, predictive maintenance for rolling stock, and e-



corridor simulation). Its purpose is to enable standardised, interoperable and scalable deployment of predictive and circularity-oriented practices in PT fleets and infrastructure.

3.1 Objective

The overarching objective of the CE4CE solution is to provide an integrated and transferable framework that enables public transport operators and authorities to transition towards a **data-driven and circular management approach** for infrastructure, rolling stock and energy systems.

Rather than focusing on a single tool, the CE4CE approach combines complementary solutions into a **coherent system**, linking strategic planning, technical analysis and operational implementation. This allows circular economy principles to be systematically embedded into existing decision-making and operational processes.

The specific objectives of the overarching solution are:

- to **operationalise circular economy principles** in public transport through practical and applicable methods and tools,
- to **improve decision-making processes** through data-driven analytics, simulation models and standardised KPI frameworks,
- to **increase efficiency and resource optimisation** through predictive maintenance, optimised energy use and extended asset lifecycles,
- and to **support scalability and transferability**, enabling the solutions to be applied across different operational and institutional contexts.

This document fulfils an integrative role by defining the common logic, architecture and functioning of the CE4CE solutions, while detailed methodologies and implementations are provided in the annexed pilot solutions.

3.2 Scope

The CE4CE solution covers an integrated approach to improving planning, operation and maintenance of public transport systems in line with circular economy principles.

The scope includes:

- **strategic planning and governance**,
including KPI-based frameworks and scenario development,
- **technical analysis and data-driven decision support**,
including predictive maintenance, sensor-based monitoring and simulation models (e.g. digital twins),
- **operational implementation**,
including organisational processes, maintenance workflows and integration into existing systems.

The solution therefore addresses all key layers of a modern, data-driven public transport system and ensures a consistent link between planning, analytics and implementation.

This overarching document does not include detailed technical specifications or pilot-specific implementation descriptions. These are provided in the annexed pilot solutions:



- **Annex 1:** Operational predictive maintenance implementation (LVB Leipzig)
- **Annex 2:** Technical and analytical modules including simulation (ATB Bergamo)
- **Annex 3:** Circular business planning and KPI-based planning framework (PKA Gdynia)

The focus of this document is therefore on the **integration of these components into a unified framework** and on their transferability and scalability.

3.3 Target groups

The CE4CE solution addresses a wide range of stakeholders involved in the planning, operation and development of public transport systems.

Primary target groups include:

- Public transport operators
(in particular asset management, maintenance, operations, planning and IT departments),
who can use the solutions to improve operational performance, maintenance strategies and investment decisions.
- Public transport authorities and policymakers,
who require reliable, data-driven evidence for strategic planning, regulation and funding decisions.

Secondary target groups include:

- Technology providers and system integrators,
who can incorporate the modular solution components into products and services,
- Research institutions and consultancy organisations,
who contribute to further development, evaluation and dissemination of the solutions.

Wider beneficiaries include European cities and regions seeking to improve their transport systems according to circular economy principles and benefiting from the validated approaches developed within CE4CE.

4. Joint solution architecture (high-level description)

4.1 Joint solution logic

The solutions developed within CE4CE are based on the key insight that circular economy principles in public transport cannot be effectively implemented through isolated measures. Instead, they require an **integrated interaction between planning, analytics and operations**.

In practice, several challenges can typically be observed:

- Strategic objectives and circular economy concepts are defined but not embedded into operational processes.
- Data on asset condition, energy flows and lifecycle performance exists but is not systematically used.
- Decisions are often taken reactively or based on incomplete information.



The CE4CE solution addresses this fragmentation through a **holistic approach** that connects all key layers of decision-making in public transport. The objective is to establish a consistent system in which:

- **planning defines objectives and priorities,**
- **data and analytics provide evidence,**
- **and operational processes ensure implementation.**

Through this integration, circular economy evolves from a strategic concept into a **practical, data-driven management approach**.

4.2 Layered solution architecture

The CE4CE solution follows a structured, layered architecture consisting of three complementary levels:

1. Planning and Governance Layer

This layer forms the strategic foundation of the solution and includes:

- definition of objectives and priorities,
- selection and structuring of relevant KPIs,
- development of scenarios for infrastructure, operations and energy systems.

Its purpose is to create a **consistent, transparent and comparable decision framework** that integrates circular economy principles into planning processes.

This layer is described in detail in **Annex 3 - Circular business planning and KPI-based planning framework (PKA Gdynia)**.

2. Technical and Analytical Layer

The second layer provides the data-driven basis for decision-making. It includes:

- continuous data acquisition through sensors,
- predictive maintenance approaches for infrastructure and rolling stock,
- simulation-based models such as digital twins and energy flow simulations.

These components enable:

- early detection of wear and system degradation,
- real-time assessment of system performance,
- analysis of alternative operational and investment scenarios.

This layer acts as the **link between planning and operations**, translating data into actionable insights.

It is described in detail in **Annex 2 - Predictive Maintenance and Simulation Modules (ATB Bergamo)**.

3. Operational Implementation and Integration Layer



The third layer focuses on the practical integration of the solution into real-world operations, while also demonstrating how technical and analytical components - including AI-based detection and condition analysis - can be effectively combined and operationalised within an organisational context.

It includes:

- integration into existing IT systems (e.g. asset management, GIS),
- adaptation of maintenance workflows and organisational processes,
- definition of roles, responsibilities and decision-making procedures,
- and the structured use of analytical outputs for operational and strategic decision-making.

Its objective is to ensure that data-driven insights are translated into **effective operational actions**, while establishing the organisational conditions required for long-term, scalable implementation.

This layer therefore not only represents the execution level but also demonstrates the **full integration of the CE4CE solution in practice**.

It is described in detail in **Annex 1 - Operational Predictive Maintenance Implementation (LVB Leipzig)**.

To clarify how the layered architecture relates to the three pilot solutions, Table 1 provides a simplified mapping between the architecture layers, their main functions and the corresponding pilot implementations.

Architecture layer	The purpose of the layer	Main pilot example/ annex	Type of layer
Planning and Governance Layer	Defines objectives, KPIs, scenarios and strategic priorities for circular public transport planning	PKA Gdynia/ Annex 3	Strategic layer: it explains what should be achieved and how progress can be measured
Technical and Analytical Layer	Collects and processes data, applies predictive maintenance, simulations and digital twins	ATB Bergamo/ Annex 2	Evidence layer: it turns data into analysis, forecasts and decision-support information
Operational Implementation and Integration Layer	Embeds analytical outputs into IT systems, maintenance workflows, roles and daily operations	LVB Leipzig/ Annex 1	Implementation layer: it shows how insights become concrete operational actions

Table 1 Clarification of the CE4CE layered architecture and its relation to pilot solutions

4.3 Interaction between layers

The key value of the CE4CE solution lies not in individual components, but in their **interaction**.

The three layers are interconnected as follows:

- The **planning layer** defines targets and strategic direction.
- The **analytical layer** provides data and evidence to assess performance and compare options.
- The **operational layer** implements measures and continuously generates new data.



This creates a **closed feedback loop**, enabling continuous improvement and supporting the long-term implementation of circular economy principles.

4.4 Core functional components

Across all layers, the CE4CE solution includes several recurring functional building blocks:

- **data acquisition and integration**
(sensor data, vehicle data, energy data, operational data)
- **analytical methods and models**
(predictive maintenance, AI-based analytics, simulation tools)
- **visualisation and decision support**
(dashboards, heatmaps, KPI systems)
- **organisational and process integration**
(workflows, roles and governance structures)

These components are modular and can be implemented step by step depending on the maturity and specific context of a transport operator.

The Leipzig pilot provides a comprehensive example of how these components - including data acquisition and AI-based analytical methods - can be combined and embedded into operational practice, illustrating the transition from isolated functionalities to an integrated system.

5. Core modules and functional blocks

The CE4CE solution is structured around a set of clearly defined functional modules that together form an integrated system for planning, analysis and operational management in public transport. These modules are **modular, interoperable and scalable**, allowing flexible adaptation to different organisational and technical contexts.

To support the transition from the high-level architecture to the detailed module description in Chapter 5, Table Y clarifies how the core functional components are translated into practical modules and where they are further explained in this document.

Core functional component	Functional role within the CE4CE solution	Corresponding module in Chapter 5	Primary pilot reference
Data acquisition and integration	Establishes the empirical basis of the solution through the systematic collection, harmonisation and integration of data from vehicles, infrastructure, energy systems and operational processes.	5.1 Data collection modules	LVB Leipzig; ATB Bergamo



Data processing and analytical methods	Converts collected data into structured analytical outputs by applying predictive maintenance algorithms, AI-based pattern recognition, simulation models and digital twin approaches.	5.2 Data processing and analytical modules	ATB Bergamo; LVB Leipzig
Visualisation and decision support	Translates analytical outputs into accessible decision-support formats, including dashboards, georeferenced visualisations, alerts, reports and KPI-based information displays.	5.3 Visualisation and decision support modules	All pilot solutions
Planning and decision-making support	Provides a structured basis for strategic and operational decision-making through KPI frameworks, scenario development and comparative assessment of planning options.	5.4 Planning and decision-making modules	PKA Gdynia
Organisational and workflow integration	Ensures that analytical outputs are embedded into existing IT environments, maintenance workflows, responsibilities, coordination routines and feedback processes.	5.5 Integration and workflow modules	LVB Leipzig

Table 2 Clarification of core functional components and their link to Chapter 5 modules

5.1 Data collection modules

The foundation of the CE4CE solution is the systematic collection of relevant data across the public transport system.

This includes:

- **infrastructure data** (e.g. track condition, overhead lines),
- **vehicle data** (e.g. CAN-bus signals, driving behaviour, energy consumption),
- **energy data** (e.g. energy flows, recuperation, losses),
- and **operational data** (e.g. schedules, disruptions, utilisation).

Data is typically acquired through sensor-based systems integrated into vehicles and infrastructure. A key feature is the use of **vehicles in regular operation as mobile sensing platforms**, eliminating the need for dedicated inspection runs.

These modules are primarily demonstrated in **Annex 2 (ATB Bergamo)** and **Annex 1 (LVB Leipzig)**.

5.2 Data processing and analytical modules

The collected data is processed through analytical methods that enable structured interpretation and evaluation. These include:

- **predictive maintenance algorithms** for early fault detection,
- **AI-based analytics** for pattern recognition and classification,
- **simulation models and digital twins**, particularly for energy flow analysis,
- and models for assessing asset condition and system performance trends.



These modules transform raw data into **actionable insights**, supporting informed decision-making and forward-looking planning.

These modules are primarily demonstrated in Annex 2 (ATB Bergamo) and are also applied and validated in operational contexts in Annex 1 (LVB Leipzig).

5.3 Visualisation and decision support modules

Analytical results are made accessible through visualisation and decision-support tools. Typical elements include:

- **dashboards and graphical user interfaces**,
- **georeferenced visualisations** (maps, heatmaps),
- **alert and early warning systems**,
- and structured reports and export formats.

These modules translate complex data into **user-friendly information**, enabling both operational and strategic use.

They are present across all pilot solutions.

5.4 Planning and decision-making modules

An essential component of the CE4CE solution is the support of structured planning and decision-making processes. This includes:

- **KPI-based governance frameworks**,
- structured selection and definition of indicators,
- and scenario development and evaluation tools.

These modules enable:

- alignment between strategic objectives and operational actions,
- comparability between different planning options,
- and long-term, evidence-based decision-making.

This functionality is primarily detailed in **Annex 3 (PKA Gdynia)**.

5.5 Integration and workflow modules

The final set of modules ensures the integration of all components into organisational structures and operational processes. This includes:

- integration into existing IT systems (e.g. asset management, GIS),
- definition of **workflows** (e.g. detection → assessment → action),
- establishment of **roles and responsibilities**,
- and routines for coordination, feedback and continuous improvement.



These modules ensure that analytical outputs are effectively translated into **concrete actions and decisions**.

They are particularly demonstrated in **Annex 1 (LVB Leipzig)**, which provides a comprehensive example of **full system integration in practice**.

5.6 Interaction of modules

The modules are designed as an **integrated system**, where:

- data collection provides the foundation,
- analytics generate insights,
- visualisation and planning translate these into decisions,
- and integration modules ensure implementation.

This modular yet interconnected structure supports both **incremental adoption** and the development of a fully integrated solution.

6. Governance model (cross-pilot)

The governance model of the CE4CE solution defines the roles, responsibilities and collaboration structures across all partners, ensuring that the developed solutions are sustainable, scalable and transferable beyond the project duration.

The purpose of the governance model is to integrate the different competencies of the project partners into a **coherent framework for development, decision-making and long-term use** of the solution.

6.1 Roles and responsibilities

The development and implementation of the CE4CE solution is based on a clear allocation of roles among project partners:

- **Public transport operators (LVB, ATB, PKA)**
take the lead in their respective pilot domains and are responsible for the practical application, validation and integration of the solutions within real operational environments.
- **Methodological and academic partners (e.g. UG)**
support the development through structured analysis, methodological frameworks and scientific input, contributing to the systematisation and comparability of the solutions.
- **Technology partners (e.g. Kruch, analytics providers)**
provide specialised technical components, algorithms and software solutions, and contribute to system development, implementation and validation.

This distribution of roles ensures that both technical innovation and operational relevance are addressed effectively.



6.2 Collaboration and decision structures

In addition to defined roles, the governance model is based on established collaboration and coordination mechanisms. Key elements include:

- **regular coordination formats**
(e.g. project meetings, workshops, operational coordination routines),
- **co-design processes**
integrating perspectives from technical, operational and management domains,
- **structured decision-making processes**
addressing both technical and organisational aspects,
- and **feedback and learning mechanisms**
allowing lessons from pilot implementations to be continuously incorporated into solution development.

These structures enable close collaboration and support adaptive, iterative improvement.

6.3 Data governance and responsibility models

Data governance is a central component of the overall governance framework. Key principles include:

- **data ownership and sovereignty of transport operators,**
- clear definition of **data access rights, responsibilities and usage,**
- and compliance with **data protection, cybersecurity and regulatory requirements.**

In addition, roles are defined for maintaining data models, ensuring data quality and interpreting analytical results, supporting reliable and consistent use of the system.

6.4 Long-term sustainability and evolution

The governance model is designed to ensure that the CE4CE solution remains usable and adaptable beyond the project duration. This includes:

- **coordinated updates and further development** of system components (e.g. algorithms, data models, interfaces),
- **standardisation of approaches and processes** to facilitate wider adoption,
- and the creation of a foundation for **future cooperation and scaling.**

Through these elements, the CE4CE solution is positioned not merely as a project outcome, but as a **sustainable and evolving approach** for circular public transport management.



7. Standardised data model and interoperability

The CE4CE solution is based on a standardised and modular data model that enables consistent, **interoperable and scalable data** use across public transport systems. It integrates structured data models, clearly defined interfaces and governance principles into a coherent framework supporting both technical integration and organisational adoption. At its core, the data model relies on unified data structures, including unique object identifiers, georeferenced asset information, timestamps and metadata. These elements ensure consistent linkage between infrastructure assets, vehicles and analytical results, and allow reproducible analysis across time and systems. Building on this, the solution defines standardised interfaces and data exchange formats that connect data acquisition systems, analytics platforms and asset management environments. This enables continuous data flows from sensor-based monitoring to operational decision-making and supports integration with systems such as GIS and asset management tools.

A key design principle is **interoperability through functional separation**: data acquisition, data processing and analytics are clearly separated, allowing independent evolution of components and avoiding vendor lock-in. This principle has been validated in the pilot implementations, particularly in Leipzig.

To ensure practical applicability, the data model aligns with **existing sector standards and regulatory requirements**. This includes **compatibility with established transport data structures**, data governance principles and relevant technical standards, supporting integration into existing and future system environments.

Together, these elements form the **foundation for scalability and transferability**. The combination of standardised data structures, interoperable interfaces, modular system design and validated operational processes **enables replication across different cities and transport operators**, as well as the integration of additional modules and functionalities.

8. Cross-pilot validation and evidence base

The CE4CE solution is not based solely on conceptual approaches but has been developed and validated through pilot implementations under real operational conditions. These pilot actions form the empirical foundation of the solution and provide evidence of its technical feasibility, organisational applicability, and strategic relevance.

The purpose of cross-pilot validation is to test the developed modules and approaches across different contexts and to demonstrate that the underlying system logic is applicable beyond local conditions.

8.1 Validation approach

Validation was carried out through the implementation of the CE4CE solution in three complementary pilot actions, each addressing a specific layer of the overall system:

- **strategic planning and kpi-based governance,**
- **technical analysis and data-driven decision support,**
- **and operational implementation and organisational integration.**



This approach enabled not only the validation of individual components, but also of the solution as an **integrated system**.

8.2 Evidence from pilot implementations

Leipzig (LVB) - Operational Integration and Implementation

The Leipzig pilot demonstrates the implementation of predictive maintenance within real operational conditions. Key validated aspects include:

- continuous, vehicle-based data collection in regular service,
- successful integration of sensors, data platforms and analytics tools,
- transformation of analytical outputs into operational maintenance decisions,
- and the establishment of organisational routines and governance structures.

This pilot provides a practical example of how the CE4CE solution can be fully integrated into a transport operator's operations.

Bergamo (ATB) - Technical and Analytical Validation

The Bergamo pilot focuses on validating analytical and simulation components. Key outcomes include:

- continuous condition monitoring using sensor-based systems,
- application of predictive maintenance to detect early-stage degradation,
- implementation of a digital twin for energy flow simulation,
- and the ability to test and optimise operational scenarios in a virtual environment.

This pilot confirms the robustness of data-driven analytics and simulation as a basis for decision-making.

Gdynia (PKA) - Strategic Planning and KPI Framework

The Gdynia pilot addresses the strategic and planning layer of the solution and demonstrates:

- structured KPI selection and configuration,
- development of consistent planning frameworks for electrified transport systems,
- and the translation of circular economy objectives into measurable indicators.

This pilot contributes to improved comparability and governance of planning processes.

8.3 Overall validation results

The combined results of the three pilots demonstrate that the CE4CE solution is:

- technically functional,
- organisationally implementable,
- and capable of delivering measurable benefits for planning, operations and maintenance.



Importantly, the pilots show that the modules provide the greatest value when combined into a **coherent system approach**.

8.4 Key transferable insights

The cross-pilot validation enables the identification of key insights applicable beyond the pilot contexts:

- the combination of analytics, simulation and KPI-based planning is essential for effective circular economy implementation,
- integration into organisational processes is as critical as technical performance,
- and modular system design significantly facilitates adaptation to different contexts.

These insights form the foundation for the scalability and transferability of the CE4CE solution.

9. Implementation blueprint (adoption guide)

The implementation blueprint provides a structured approach for adopting the CE4CE solution in other cities and transport organisations. Its objective is to offer a practical guide that supports step-by-step implementation while allowing flexibility for different contexts.

The approach is based on lessons learned from the pilot projects and is designed to be **modular, scalable and adaptable**.

9.1 Key principles for implementation

The implementation of the CE4CE solution is based on a set of practical principles derived from the pilot applications in Leipzig, Bergamo and Gdynia. Rather than aiming for full system deployment from the outset, the solution follows a stepwise and use-case-driven approach, allowing operators to start with selected modules (e.g. infrastructure monitoring or KPI-based planning) and expand gradually. A key principle is the alignment of technical systems with organisational processes. The pilots have shown that the value of data-driven analytics depends on their integration into maintenance workflows, asset management structures and decision-making routines. Furthermore, the solution must be adapted to local technical and institutional conditions, including existing IT systems, data availability and organisational responsibilities. Early and continuous involvement of end users - particularly asset management, maintenance and operations - is critical to ensure acceptance, usability and effective integration into daily processes. Together, these principles ensure that the implementation is not only technically feasible, but also operationally effective and sustainable in the long term.

1.1 Implementation phases

The implementation can be structured into a set of iterative phases, reflecting both technical deployment and organisational integration.

Phase 1 - Preparation and Objective Setting



This phase includes the assessment of existing systems, data availability and organisational processes. Based on this, specific use cases and objectives are defined (e.g. early detection of infrastructure faults, improved maintenance planning). Initial KPIs and scope are selected.

Phase 2 - Technical and Organisational Setup

The required data infrastructure is prepared, including data models, interfaces and object identifiers. At the same time, roles, responsibilities and governance structures are defined to ensure alignment between technical systems and operational processes.

Phase 3 - Pilot Implementation

Selected modules are deployed under real operational conditions. This phase includes data collection, analytical processing (e.g. AI-based detection) and validation of results through field inspections and user feedback. Iterative refinement of algorithms, dashboards and workflows is essential.

Phase 4 - Integration and Scaling

The solution is integrated into existing IT systems (e.g. asset management, GIS) and operational workflows. Maintenance and planning processes are adapted to use the generated insights, and training and capacity building are carried out to support adoption.

Phase 5 - Institutionalisation and Continuous Improvement

In this phase, the solution becomes part of regular operations. This includes the establishment of routines such as KPI-based reviews, continuous improvement of data quality and analytics, and gradual expansion to additional network sections, assets or use cases.

1.2 Modular adoption pathways

The CE4CE solution allows different entry points depending on the maturity level, strategic priorities and technical capabilities of a transport operator. A planning-driven approach (PKA Gdynia) starts with the definition of KPIs and decision-making frameworks, enabling operators to structure their strategic objectives and prioritise investments before introducing technical systems. An analytics-driven approach (ATB Bergamo) focuses on the introduction of monitoring and simulation tools, such as sensor-based data collection and digital twins, to generate insights on infrastructure condition and energy flows as a basis for optimisation. An operations-driven approach (LVB Leipzig) begins with the integration of predictive maintenance into existing workflows, combining data acquisition, AI-based detection and organisational processes to directly improve maintenance practices under real operational conditions. These pathways are not isolated but can be combined and expanded over time, allowing operators to progressively develop a fully integrated system tailored to their specific context.

1.3 Key success factors

The pilot implementations highlighted several key success factors for the successful adoption of the CE4CE solution.



A fundamental requirement is **high data quality** and, in particular, **robust and stable data pipelines**. The pilots showed that consistent data availability, reliable georeferencing and well-defined object identifiers are more critical than maximum sensor precision.

Clear governance structures and defined roles are essential to ensure that data, analytics and operational actions are effectively linked. This includes the alignment between asset management, maintenance and IT functions.

Strong cross-department collaboration is a prerequisite for integrating data-driven approaches into real operations. Regular coordination routines, such as joint reviews and validation processes, support continuous learning and system improvement.

Finally, **continuous feedback and iteration** are key to achieving maturity. Analytical models, dashboards and workflows must be refined based on real operational experience, including field validation of detected events and ongoing adjustment of thresholds and parameters.

10. Transferability and replicability model

The transferability and replicability model of the CE4CE solution defines how the developed approaches can be applied in other cities, transport organisations and institutional environments depending on the starting point and maturity level of an external organisation. Its objective is to position the CE4CE outcomes as a **scalable and transferable model across Europe**. While the implementation blueprint describes how the CE4CE solution can be introduced within an organisation, this section focuses on its transferability and replication across different technical, organisational and institutional contexts.

1.4 Core principles of transferability

From a transfer perspective, these principles describe the characteristics of the CE4CE solution that enable its adaptation beyond the original pilot environments.

The CE4CE solution is designed around key principles that enable its application in different contexts:

- **modularity**,
allowing independent adoption of solution components such as KPI-based planning, monitoring systems or predictive maintenance modules,
- **technological openness**,
based on standardised data models, open interfaces and the functional separation between data acquisition and analytics, avoiding vendor lock-in,
- **organisational compatibility**,
ensuring that data-driven approaches can be integrated into existing maintenance workflows, asset management structures and decision-making processes,
- **and scalability**,
enabling gradual expansion from initial pilot applications to network-wide and system-wide implementation.



1.5 Replication pathways

Different replication pathways are possible, depending on the starting point and maturity level of the organisation:

1. Modular replication

Operators may start by adopting individual components, such as KPI-based planning tools (PKA), analytical and simulation modules (ATB), or operational predictive maintenance approaches (LVB).

2. Stepwise system integration

Based on initial modules, organisations can progressively expand towards a complete system by connecting data acquisition, analytics and operational processes.

3. Full system adoption

Organisations with advanced capabilities may directly implement an integrated architecture combining planning, analytics and operational integration.

10.1 Preconditions for successful replication

Successful transfer requires several enabling conditions beyond the initial implementation steps, particularly when applying the solution in a different organisational and technical context:

Technical conditions

- access to relevant data sources
- appropriate IT infrastructure
- minimum data quality standards

Organisational conditions

- clearly defined roles and responsibilities
- cross-functional collaboration
- openness to process adaptation

Institutional conditions

- support from management and policymakers
- availability of funding mechanisms
- alignment with strategic objectives

10.2 Scaling potential

The CE4CE solution demonstrates strong scaling potential:

- **horizontal scaling**
(expansion across networks, fleets or cities)
- **vertical scaling**
(addition of advanced functionalities)



- **cross-system scaling**
(application to different transport modes and infrastructures)

10.3 Added value within the European context

The model delivers clear benefits in European public transport systems by:

- supporting climate and circular economy objectives,
- improving resource efficiency,
- and strengthening data-driven governance.

It therefore contributes directly to broader European policy goals in sustainable mobility.

11. Consolidated feedback synthesis

The development of the CE4CE solution was strongly supported by structured feedback collected from pilot implementations, expert reviews and collaborative development formats. This feedback was systematically analysed and incorporated into the continuous refinement of the solution components.

The objective of this process is to improve usability, technical robustness and practical applicability, while strengthening the transferability of the solution.

11.1 User feedback from pilot implementations

Feedback from operational users in the pilot projects played a key role in improving the solution. Significant improvements were achieved in:

- **dashboard usability and user interfaces**,
through clearer structure, improved visualisation and easier interpretation,
- **data clarity and transparency**,
through standardised formats, consistent units and clear KPI definitions,
- **refinement of alerting and detection logic**,
reducing false positives and improving prioritisation,
- and **integration into operational workflows**,
ensuring smooth adoption in real-world processes.

This feedback ensures that the solution is not only technically sound but also accepted and effectively used in practice.

11.2 Expert feedback and technical validation

Further improvements were driven by input from technical and methodological experts. Key contributions include:



- refinement of analytical algorithms,
- definition and standardisation of interfaces,
- and enhancement of data validation and quality control mechanisms.

This input has strengthened the technical reliability and consistency of the solution.

11.3 Collaborative development formats

Additional insights were generated through collaborative development formats, including workshops and joint design sessions, which supported the development of innovative visualisation and user interaction concepts.

These formats contributed to improvements in user interface design, system interaction, and overall user-centricity of the solution.

11.4 Overall contribution of feedback integration

The systematic integration of feedback from multiple sources has significantly enhanced the CE4CE solution.

It has led to:

- improved alignment with user needs,
- continuous refinement of technical components,
- and stronger focus on usability and transferability.

This feedback-driven approach is a key element in establishing the solution as a **robust, user-oriented and scalable system**.

12. Expected impact and added value

The CE4CE solution aims to generate measurable improvements in planning, operations and maintenance of public transport systems. By combining data-driven analytics, simulation-based planning and operational integration, it provides a comprehensive approach to implementing circular economy principles.

12.1 Operational impact

On an operational level, the solution enables:

- early detection of wear and failures,
- reduction of unplanned interventions and disruptions,
- and more efficient maintenance planning and execution.

This improves system reliability and stabilises daily operations.



12.2 Economic impact

The solution contributes to economic efficiency through:

- **reduced maintenance and repair costs,**
- **improved investment planning based on data,**
- **and optimised lifecycle cost management (total cost of ownership).**

This leads to more efficient use of financial resources over time.

12.3 Environmental and circularity impact

A key added value lies in its contribution to circular economy goals:

- **extended asset lifetime,**
- **reduced material consumption and waste,**
- **and improved energy efficiency,** including better use of recuperated energy.

These effects support climate and sustainability objectives.

12.4 Strategic impact

The CE4CE solution strengthens long-term decision-making capabilities:

- **data-driven planning and governance,**
- **improved scenario comparability,**
- **and integration of circular economy objectives into strategic frameworks.**

This enables more structured and resilient system management.

12.5 Organisational impact

Implementation leads to organisational transformation:

- **stronger cross-department collaboration,**
- **development of data-related competencies,**
- **and more structured roles and processes.**

This supports the transition towards data-driven organisations.

12.6 European added-value

The CE4CE solution contributes to European policy objectives by:

- **supporting Green Deal and circular economy goals,**
- **fostering digital transformation in public transport,**



- and improving **resource efficiency in existing systems**.

Its modular nature allows for replication and scaling across Europe.

13. Annexes

Annex 1: CE4CE D3.1.2 Annex 1_LVB_Solution.pdf

Operational predictive maintenance implementation (LVB Leipzig)

Detailed description of the Leipzig pilot, demonstrating the operational implementation of predictive maintenance, including vehicle-based data acquisition, AI-supported analytics and integration into maintenance workflows.

Annex 2: CE4CE D3.1.2 Annex 2_ATB_Solution.pdf

Technical and analytical modules including simulation (ATB Bergamo)

Presentation of the Bergamo pilot, focusing on technical and analytical modules such as sensor-based monitoring, predictive maintenance and digital-twin-based energy simulation.

Annex 3: CE4CE D3.1.2 Annex 3_PKA_Solution.pdf

Circular business planning and KPI-based planning framework (PKA Gdynia)

Description of the Gdynia pilot, providing a KPI-based planning framework to support strategic decision-making and the integration of circular economy principles in public transport systems. The tool is available publicly at: <https://ce4ce.ug.edu.pl/>

Annex 4: CE4CE Handbook on pilots and solutions

This handbook documents and disseminates the key pilot actions and solutions developed within CE4CE, providing practical insights and guidance for stakeholders seeking to apply circular economy principles in public transport contexts. The handbook is publicly available in English and in all Central European languages on the CE4CE website under the Outputs section: <https://www.interreg-central.eu/projects/ce4ce/?tab=outputs>. The English version can be directly accessed here: [CE4CE_Handbook_Pilots_Solutions_EN.pdf](https://www.interreg-central.eu/projects/ce4ce/?tab=outputs)