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ReBuilt

D.2.3.4: Summary Report on Testing of Digital Tools

INFORDATA with other
Interreg CE ReBuilt partners

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Contents

Executive Summary

Deliverable 2.3.4 presents the comprehensive summary report on the pilot testing of all digital tools developed within the ReBuilt project (CE0100390) framework, as required by Activity 2.3 of the approved Grant Agreement. Following the development and deployment of the digital material traceability platform documented in D2.3.1, and the GAIA-X use case implementation reported in D2.3.5, this deliverable evaluates the technical functionality, interoperability, system performance, and user acceptance of the solutions implemented by INFORDATA SISTEMI SRL in collaboration with project partners during Reporting Period 6 (Months 31–36).

The testing phase was conducted in a real-world operational environment, primarily at the NIGRAD demonstration centre in Maribor, Slovenia, assessing the complete material value chain from demolition and waste collection through processing, quality assessment, and reuse. The pilot validates the full scope of Activity 2.3, covering the equipping of materials with RFID identification technology; the generation and cryptographic signing of Digital Product Passports (DPP) in alignment with the UN/CEFACT DPP 0.6.0 standard; the integration of DPPs into Building Information Modelling (BIM) workflows; and the interoperability of the platform with the H2020 CINDERELA digital on-line market (CinderOSS). A key performance target established in the Grant Agreement – achieving a minimum of 20 successful matches between material and waste producers and potential buyers on the CinderOSS platform – was set as a measurable benchmark for the pilot.

The pilot testing successfully validated the end-to-end implementation of the GAIA-X use case, confirming functional Decentralised Identifiers (DID) using the did:web method, verifiable Gaia-X Participant Credentials generated through the official onboarding wizard, and cryptographically signed Digital Product Passports using JsonWebSignature2020. These capabilities enable any external party to independently verify material provenance without reliance on centralised ReBuilt infrastructure, realising the core European data sovereignty principles embedded in the GAIA-X Trust Framework.

The system architecture – built on the Yii2 PHP framework with a centralised MySQL database and RESTful API – demonstrated reliability under load conditions representative of multi-hub operational deployment. Mobile field applications supporting RFID, NFC, and QR code scanning were validated across environments with varying network connectivity, confirming the robustness of the platform's offline synchronisation mechanisms.

The results confirmed that the digital tools are technically robust, interoperable across European digital infrastructure frameworks, and operationally ready to support the deployment of the network of Regional Circular and Digital Construction Hubs (Output 3.3). This deliverable validates Output 2.2 (Circular construction digital pilots) and Output 2.4 (Digital solutions for circular construction) as defined in the Grant Agreement.

Table ES-1: Summary of Key Testing Results

Testing Area	Grant Agreement Target	Result
CinderOSS marketplace matches	≥ 20 matches	22

Testing Area	Grant Agreement Target	Result
Gaia-X Participant Credential	Operational DID and VC	Achieved (did:web:rebuilt.infordata.eu)
Digital Product Passport generation	Cryptographically signed DPPs	Achieved (JsonWebSignature2020)
BIM integration (IFC export)	IFC-compliant data export	Autodesk Revit 2024 and Graphisoft Archicad 27.
Mobile application (RFID/NFC/QR)	Field-operational tracking	Validated at NIGRAD
Offline synchronisation	Reliable field operation	Validated with conflict resolution
Stakeholder UAT participation	Multi-stakeholder validation	6 distinct stakeholder organizations across 4 countries.

1. Introduction

The ReBuilt project (CE0100390) is co-funded under the Interreg Central Europe 2021-2027 Programme, Priority 2 (A more social and inclusive Central Europe), Specific Objective 2.3 (Taking circular economy forward in central Europe). With a total project duration of 36 months (M1-M36), ReBuilt addresses the construction sector's systemic need for circular economy transformation across the Central European programme area, encompassing Austria, Croatia, Czech Republic, Germany, Hungary, Italy, Poland, Slovakia, and Slovenia.

The construction industry accounts for approximately 40% of EU energy consumption, 36% of CO_2 emissions, and generates over 35% of total waste. The absence of digital material traceability infrastructure represents a critical bottleneck for realising circular economy objectives: materials cannot be efficiently reused or recycled if their composition, origin, quality, and provenance cannot be reliably documented and communicated across organisational and national boundaries.

Activity 2.3 of the ReBuilt Grant Agreement tasks INFORDATA SISTEMI SRL (PP5) with leading the development of a digital solution for the digitalisation of circular value chains, incorporating material passports, digital identification technologies, and integration with the pan-European CinderOSS marketplace. Building on prior work from the Interreg Italy-Slovenia Retracking project, Activity 2.3 upscales and extends a digital business ecosystem from a single production plant to the full upstream and downstream value chain at the NIGRAD demonstration centre.

Deliverable 2.3.4 is the culminating summary report for Activity 2.3, integrating findings from all preceding deliverables in the activity stream:

- **D2.3.1** – Testing the digital material passports and BIM interoperability (Period 5, M25–M30): comprehensive platform documentation, BIM integration implementation, and database schema.
- **D2.3.2** – Digital value chain and business ecosystem (Period 5, M25–M30): value chain modelling and cross-sectoral bio-concrete use case.
- **D2.3.3** – Operating on-line digital marketplace for circular construction (Period 6, M31–M36): full CinderOSS deployment and marketplace operations.
- **D2.3.5** – Development of GAIA-X use case (Period 6, M31–M36): Gaia-X federated identity, Verifiable Credentials, and DPP signing architecture.

This report focuses on the testing outcomes: the methodologies applied, the operational scenarios executed, the performance metrics collected, and the lessons learned during Period 6. It provides an evidence base confirming that the digital tools are ready for operational deployment and broad dissemination through the Regional Circular and Digital Construction Hub network.

1.1 Scope and Objectives of the Testing Phase

The primary objective of the testing phase was to validate the operability, data-sharing capabilities, and user acceptance of the fully integrated digital business ecosystem. Specific testing objectives included:

- Verifying end-to-end material traceability from waste production through processing to reuse, including generation and cryptographic signing of Digital Product Passports.
- Validating the interoperability of the platform with external digital infrastructure: BIM ecosystems, Gaia-X federated networks, and the CinderOSS marketplace.
- Confirming the reliability of mobile field applications under real-world operational conditions, including areas of limited network connectivity.
- Achieving the Grant Agreement target of at least 20 successful matches between material/waste producers and potential buyers on the CinderOSS platform.
- Assessing user acceptance across diverse stakeholder groups with varying levels of digital literacy.
- Documenting technical challenges, operational lessons, and recommendations for future scaling and replication.

1.2 Document Structure

Section 2 provides basic information about the digital solution. Section 3 describes the use case scenario and stakeholder ecosystem. Section 4 covers system architecture and performance testing. Section 5 documents integration testing results for BIM, Gaia-X, and CinderOSS. Section 6 presents platform functionality and user acceptance testing outcomes. Section 7 analyses challenges and lessons learned. Section 8 presents conclusions and next steps.

2. Basic Information about the Digital Solution

2.1 Solution Overview and Design Philosophy

The digital solution tested in Period 6 is a modular, cloud-based platform developed by INFORDATA SISTEMI SRL for the management of construction material lifecycles within circular economy frameworks. The platform is built on the Yii2 PHP framework with a centralised MySQL database, exposing a RESTful API architecture that supports integration with external systems through standardised interfaces. The system is deployable as a Software as a Service (SaaS) offering, enabling multi-tenant operation across the network of Regional Circular and Digital Construction Hubs.

The design philosophy is grounded in four principles: modularity (enabling incremental feature activation for different organisational contexts), API-first architecture (ensuring interoperability with existing and emerging digital construction tools), data sovereignty (implementing Gaia-X-compliant federated infrastructure to ensure cross-border data exchange under European standards), and field operability (supporting offline-capable mobile applications for construction and waste processing environments where network connectivity is unreliable).

The system utilises digital identification technologies – RFID, NFC, and QR codes – to enable automatic material tracking from waste production through processing to reuse. These technologies accommodate the full range of operational contexts at the NIGRAD demonstration centre and anticipated at future deployment sites, from industrial-grade RFID readers integrated with processing machinery to smartphone-based QR scanning for field operators with limited equipment.

2.2 Core System Objectives

The testing phase was designed to verify the solution's ability to achieve the core operational and technical objectives defined in the Grant Agreement and elaborated in D2.3.1:

Table 2-1: Core System Objectives and Testing Coverage

Objective	Description	Testing Coverage
Material Lifecycle Transparency	Complete traceability of materials and accuracy of generated DPPs from waste origin to reuse	Sections 3.2, 4, 6.2
Operational Efficiency	Real-time inventory tracking, mobile application usability, workflow integration	Sections 3.2, 4.2, 6.1, 6.2
GAIA-X Data Sovereignty	Verifiable Credentials, DID-based identity, cross-border data sharing compliance	Section 5.2
BIM Interoperability	IFC-compliant data export and import into BIM software ecosystems	Section 5.1

Objective	Description	Testing Coverage
CinderOSS Marketplace	Automated material listing and achievement of ≥20 producer-consumer matches	Section 5.3
Regulatory Compliance	Alignment with EU DPP regulation, EWC codes, Gaia-X Trust Framework	Sections 5.2, 7.3

2.3 Technology Stack

- **Backend Framework:** Yii2 PHP – MVC architecture with Active Record ORM, custom RESTful API controllers, and RBAC permission system.
- **Database:** MySQL – relational schema with 35 tables covering core entities, waste traceability, Digital Product Passports, quality/certification, and marketplace domains.
- **Digital Identification:** RFID (ISO 15693/18000-6C), NFC (ISO 14443), QR Code (ISO 18004) – supporting full-coverage material tagging from processing to installation.
- **Gaia-X Infrastructure:** did:web Decentralised Identifier at did:web:rebuilt.infordata.eu, JsonWebSignature2020 for DPP signing, eIDAS-aligned certificate chain, Gaia-X Compliance Credential.
- **BIM Integration:** IFC (ISO 16739) export engine for IFC 2x3/4 compliant datasets; material geometry, properties, and DPP links embedded in IfcBuildingElementProxy entities.
- **Mobile Application:** Responsive web application with offline synchronisation using IndexedDB and background sync; optimistic conflict resolution with manual override capability.
- **Deployment:** Cloud-hosted Linux server environment; containerised application stack enabling horizontal scaling for multi-hub deployment.

3. Use Case Scenario

3.1 Stakeholder Ecosystem and Roles

The pilot testing at the NIGRAD demonstration centre involved a multi-stakeholder ecosystem reflecting the real-world complexity of circular construction material flows. NIGRAD d.o.o. (PP3) is a civil engineering company with over 160 years of history, responsible for construction and maintenance of municipal infrastructure in the City of Maribor, Slovenia. NIGRAD operates both as a producer of construction and demolition waste (CDW) from its infrastructure works and as a processor and supplier of secondary materials through its recycling facility.

- **Demolition and Deconstruction Operators (NIGRAD field teams):** Responsible for mobile data capture at demolition sites using RFID scanners and the mobile web application. Tested workflow for initial material documentation, Waste Batch ID creation, and Digital Product Passport initialisation in field conditions including limited network connectivity.
- **Waste Management and Processing Coordinators (NIGRAD facility staff):** Responsible for intake registration, processing event logging, quality assessment documentation, and inventory management at the NIGRAD recycling facility. Tested the core waste traceability workflow including EWC code assignment, processing stage transitions, and material storage tracking.
- **Construction Project Managers (NIGRAD and partner staff):** Responsible for marketplace interaction, material procurement planning, and BIM model integration. Tested the CinderOSS listing workflow, search and matchmaking functionality, and IFC data export capabilities.
- **Quality Assurance Technicians (NIGRAD laboratory staff):** Responsible for recording and certifying material quality testing results including compressive strength, density, and aggregate classification. Tested the structured quality assessment forms and attachment management for CE Certificates and test reports.
- **Platform Administrators (INFORDATA technical staff):** Responsible for system configuration, user management, Gaia-X credential maintenance, and integration monitoring. Conducted load testing, API performance benchmarking, and security validation.
- **External Verifiers (IIC Slovakia, partner staff):** Responsible for independent verification of Gaia-X Participant Credentials and DPP cryptographic signatures. Validated the end-to-end Gaia-X trust chain from DID document resolution through signature verification without reliance on ReBuilt infrastructure.

The validation run engaged 6 distinct stakeholder organizations across 4 countries: NIGRAD d.o.o. (Slovenia) as CDW producer and processor; an agricultural cooperative (Slovenia) as the bio-fibre supplier; MUAS (Germany) for bio-concrete manufacturing; TUW (Austria) for quality certification; Open Content SCARL (Italy) for CinderOSS marketplace operations; and INFORDATA SISTEMI SRL (Italy) operating the ReBuilt traceability platform.

3.2 Primary Use Case: Testing Complete Material Lifecycle Management

The primary testing scenario traced the complete physical and informational lifecycle of concrete and structural elements at the NIGRAD facility. This use case encompasses all major platform capabilities and was executed across multiple testing cycles during Period 6 to validate reproducibility and system stability under varying operational conditions.

3.2.1 Material Origin and Initial Documentation

- Creation of Waste Batch IDs associated with specific demolition events, site coordinates (GPS-captured), and date-time stamps.
- Generation of initial Digital Product Passports pre-populated with waste origin data, preliminary EWC code assignment, and estimated material quantities.
- RFID antenna attachment to structural elements and concrete batches, with tag-to-record linking confirmed via scan verification.
- Offline data capture in areas with limited GSM/4G connectivity, with data queued for background synchronisation upon network restoration.

Offline data capture was validated in cases where demolition sites had limited 4G coverage, with data successfully synchronized upon return to network connectivity.

3.2.2 Transportation and Intake Processing

- Transport events correctly triggered status transitions in the waste traceability workflow state machine, updating DPP records with chain of custody information.
- Geolocation data captured during transport was correctly appended to the material audit trail.
- Multi-load transport batches (multiple Waste Production Items per transport event) were correctly associated and disaggregated at intake.

3.2.3 Processing and Quality Assesment

- Processing event logging with structured forms capturing equipment used, processing methodology, input and output quantities, and date-time stamps.
- Quality assessment data entry through laboratory-validated forms covering compressive strength (EN 13055), grain size distribution, Los Angeles coefficient, and aggregate density.
- Automatic EWC code refinement upon processing completion, updating the DPP with the secondary material classification.
- Cryptographic re-signing of the Digital Product Passport following each significant data update, maintaining a complete signed audit trail in the product_dpp_sign table.

3.2.4 Marketplace Listing and Reuse Coordination

- Automated generation of CinderOSS-compatible material listings from confirmed product records, including availability quantities, quality parameters, DPP links, and location data.

- Manual review and publication approval workflow enabling NIGRAD staff to validate listing content before public exposure.
- Matchmaking query execution from prospective buyers, with platform-mediated contact initiation and transaction logging.

8 distinct material listings were successfully published. These were mapped to 1,000 kg functional reference units spanning fractions 0-22mm, 0-32mm, and 0-63mm for concrete, asphalt, and earth excavation.

3.3 Specialised Use Cases

3.3.1 High-Value Component Recovery

Selective deconstruction scenarios involving structural steel elements and reusable concrete prefabs were tested for component-level (rather than batch-level) tracking. Individual components were assigned unique RFID tags and corresponding DPPs, enabling per-component quality documentation, dimensional data capture, and individual marketplace listing. This use case demonstrates the platform's capability to support higher-value reuse pathways alongside bulk aggregate recovery.

3.3.2 Cross-Border Data Sharing via Gaia-X

A cross-border data sharing scenario was executed with partner organisations in Italy (INFORDATA) and Slovakia (IIC) acting as external data consumers. Partners accessed DPP records published through the Gaia-X-compliant SPARQL endpoint and independently verified DPP signatures using the public key extracted from the did:web:rebuilt.infordata.eu DID document, validating the core data sovereignty claim that material passport data can be trusted without requiring direct access to ReBuilt infrastructure.

4. System Architecture

4.1 Architectural Overview and Design Principles

The system architecture tested in Period 6 implements a four-tier design pattern as documented in D2.3.1. The architecture separates concerns across the Physical Interface Layer, Application Layer, Data Management Layer, and Integration Layer, enabling independent scaling, maintenance, and evolution of each tier. The API-first design principle ensures that all platform capabilities are exposed as RESTful endpoints, enabling integration with external systems without requiring modifications to the core application.

The testing phase evaluated the architecture against three key non-functional requirements: availability (continuous operation supporting geographically distributed users across the Central European programme area), performance (acceptable response times under the concurrent user loads expected from multi-hub deployment), and resilience (graceful handling of network failures, external service outages, and conflicting concurrent data operations).

4.2 Architectural Layer Testing Results

4.2.1 Physical Interface Layer

- RFID antenna attachment durability under outdoor demolition conditions – tested with standard RFID inlays attached to concrete elements using industrial adhesive and UV-resistant encapsulation.
- Scan reliability at varying distances and orientations for RFID (ISO 15693) and NFC (ISO 14443) technologies under real-world interference conditions at the NIGRAD facility.
- QR code legibility after exposure to dust, water, and abrasion typical of construction environments.
- Mobile web application performance on Android smartphones with 4G, 3G, and offline operation modes.

For the CDW use case, HID Global IN Tag HF tags (ISO 15693) and Zebra handheld readers achieved a 98.5% read reliability rate at a 15-30 cm range. For the bio-bales, Confidex Survivor encapsulated UHF tags (ISO 18000-6C) maintained a 94% read rate at distances up to 2 meters.

4.2.2 Application Layer (Yii2 Framework)

- Role-Based Access Control (RBAC) policies – verified that operators, coordinators, quality technicians, and administrators accessed only permitted platform functions.
- Workflow state machine transitions – tested all valid and invalid state transitions for Waste Production Items through the intake → processing → quality assessment → marketplace listing lifecycle.
- Form validation rules – confirmed that mandatory fields, data type constraints, and business rule validations were correctly enforced.

- Audit logging – confirmed that all data creation, modification, and deletion events were logged with user identity and timestamp.

Implementing the parent-child data relationship exposed edge cases requiring a one-to-many batch split architecture for processing events where a single input batch is split into multiple output grades. Additionally, manual EWC code entry created a field bottleneck, which was resolved by utilising a Platform-assisted data entry approach (Option B) for bulk CSV data injection.

4.2.3 Data Management Layer (MySQL Database)

Load testing on the MySQL database was conducted to assess performance under the concurrent user and transaction volumes anticipated for multi-hub deployment. Test scenarios included simultaneous material registration by multiple field operators, concurrent API queries from BIM and CinderOSS integration endpoints, and high-volume DPP signing operations.

4.2.4 Integration Layer

- CinderOSS integration adapter: implemented with idempotent request design and local queue for failed synchronisation attempts.
- Gaia-X Clearing House adapter: implemented with fallback to cached credential presentation during Clearing House unavailability, as documented in D2.3.5.
- BIM export module: implemented as a synchronous request-response endpoint with configurable IFC version output (IFC 2x3 / IFC 4).

5. Integration with External Systems (BIM, Gaia-X, CinderOSS, Marketplaces)

5.1 Building Information Modelling (BIM) Integration Testing

BIM interoperability testing was conducted to verify that material tracking data generated by the ReBuilt platform could be seamlessly incorporated into architectural and engineering workflows. The integration targets were defined in D2.3.1 based on the IFC open standard (ISO 16739), enabling vendor-neutral exchange with the major BIM authoring environments used by project partners.

5.1.1 IFC Export Testing

The platform's IFC export engine was tested for correct generation of IFC 2x3 and IFC 4 compliant datasets. Exported IFC files contain:

- IfcBuildingElementProxy entities representing individual tracked materials and products.
- IfcPropertySets containing material properties (composition, quality parameters, EWC classification, processing history).
- IfcRelAssociatesDocument relationships linking material entities to their corresponding Digital Product Passport URLs.
- IfcOwnerHistory records providing provenance information for all entities.

IFC 2x3 and IFC 4 datasets were successfully exported and validated in Autodesk Revit 2024 and Graphisoft Archicad 27. Property mapping issues regarding EWC classifications and live DPP URLs were successfully resolved by binding them to custom IfcPropertySets without geometry loss.

5.1.2 BIM Workflow Integration

- Material scheduling: confirmed that EWC-classified materials could be queried and scheduled within BIM models using exported property data.
- DPP link persistence: verified that DPP URLs embedded in IFC files remained accessible and returned current DPP data after material status updates.
- Circular material substitution: tested the workflow for identifying available secondary materials in the platform inventory and substituting them for virgin material specifications in BIM models.

5.2 Gaia-X Federated Infrastructure Integration Testing

The Gaia-X integration testing validated the platform's compliance with European data sovereignty requirements as specified in the Grant Agreement and detailed in D2.3.5. The testing covered all three components of the Gaia-X architecture: identity infrastructure, Participant Credentials, and signed Digital Product Passport publication.

5.2.1 Identity and Trust Infrastructure Testing

- DID document resolution was verified from multiple independent networks (Italy, Slovakia, Austria) confirming public accessibility.
- JSON-LD context validation confirmed correct application of the Gaia-X ontology and W3C Verifiable Credentials context URIs.
- Public key extraction and verification confirmed that the JsonWebKey2020 key material in the DID document correctly corresponded to the private key used for DPP signing.

5.2.2 Verifiable Credentials Testing

- Successful acceptance of the Participant Credential by the Gaia-X Compliance Service (v1 production environment).
- Correct schema compliance with the Gaia-X Trust Framework, including mandatory gx:LegalParticipant, gx:ServiceOffering, and gx:compliance credential structures.
- Credential refresh and renewal procedures validated to confirm operational continuity beyond the initial certificate validity period.

Table 5-1: Gaia-X DID and Verifiable Credential Configuration (from D2.3.5)

Component	Configuration	Test Result
DID Method	did:web:rebuilt.infordata.eu	Verified – public resolution confirmed
Participant Credential Type	gx:LegalParticipant + gx:compliance	Validated by Gaia-X Clearing House
DPP Signature Algorithm	JsonWebSignature2020 (RS256)	Independently verified by IIC Slovakia
Key Type	JsonWebKey2020 (RSA 2048)	Active – eIDAS certificate chain anchored
JSON-LD Canonicalisation	URDNA2015	Deterministic across verification tools
Compliance Credential Issuer	Gaia-X Notary	Signed credential obtained

5.2.3 Digital Product Passport Signing Testing

- IIC Slovakia (PP12) acting as an independent verifier successfully resolved the DID document, extracted the public key, and cryptographically verified DPP signatures for sample material records.

- Signature verification was confirmed using three independent verification toolchains: the Gaia-X Compliance Service, a custom Python verifier, and the jsonld-signatures JavaScript library.
- DPP JSON-LD canonicalisation was confirmed to produce deterministic output across all verification toolchains, validating the URDNA2015 implementation.

5.3 CinderOSS Marketplace Integration Testing

The CinderOSS platform, managed by Open Content (PP4), serves as the H2020 CINDERELA-originated transnational marketplace for circular construction materials. A critical performance target defined in the Grant Agreement for Activity 2.3 was the utilisation of the CinderOSS platform to facilitate at least 20 matches between material/waste producers and potential buyers.

5.3.1 Marketplace Publishing Testing

- Processed material records with confirmed quality certification were automatically synchronised to CinderOSS upon operator-approved publication.
- Synchronisation payload confirmed to include material type, EWC classification, available quantity, quality parameters, location, availability date, and DPP URL.
- DPP links in CinderOSS listings were confirmed to resolve correctly to current DPP records in the ReBuilt platform.
- Update propagation tested: changes to availability quantities in the ReBuilt platform were reflected in CinderOSS listings within the configured synchronisation interval.

5.3.2 Matchmaking Results

The matchmaking functionality of the CinderOSS platform was tested through active market engagement during Period 6, involving NIGRAD as the primary material producer and construction companies in the programme area as potential buyers:

During Period 6, the ReBuilt project successfully exceeded the Grant Agreement target by facilitating a total of 22 confirmed matches between material producers and potential buyers on the CinderOSS platform. A match is defined as a confirmed expression of interest by a buyer in a specific material listing that resulted in contact initiation.

Material Types Involved: The successful matches encompassed the core materials tested within the project's primary use cases. Buyer interest and commercial discussions were distributed across:

- Recycled Concrete Aggregates: Secondary aggregates processed from CDW, spanning various grain size fractions (e.g., 0-22mm, 0-32mm, 0-63mm).
- Modular Concrete Blocks: Structural precast concrete elements recovered or produced using secondary raw materials.
- Bio-concrete Products: Natural fibre-based construction materials, including hempcrete insulation panels and bio-concrete blocks.

Geographic Distribution of Matched Parties: The matchmaking demonstrated successful cross-border connectivity across the Central European programme area. Material

producers, primarily based at the NIGRAD demonstration centre and partner agricultural sites in Slovenia, were successfully matched with a diverse geographic pool of buyers and stakeholders operating within the project's partner regions, including Slovenia, Austria, Germany (Bavaria), and Italy

A match is defined in the Grant Agreement context as a confirmed expression of interest by a buyer in a specific material listing, resulting in contact initiation through the CinderOSS platform. This definition encompasses both completed transactions and advanced negotiations at the close of the reporting period.

6. Platform Functionalities

6.1 Platform Overview and User Experience Testing

User Acceptance Testing (UAT) was conducted with representative users from each stakeholder group to evaluate the platform's usability, responsiveness, and suitability for the operational contexts of circular construction material management. The UAT protocol covered desktop web browser access (Chrome, Firefox, Edge) and mobile device access (Android smartphones, 5" to 6.5" screens), reflecting the diverse access environments of platform users.

6.1.1 UAT Methodology

- Task completion timing for core workflows (material registration, quality assessment, marketplace listing, DPP verification).
- Error rate monitoring – number of incorrect actions or system error triggers per task.
- Post-task questionnaire using a 5-point Likert scale covering interface clarity, workflow intuitiveness, and mobile performance.
- Open feedback collection on pain points and suggested improvements.

6.1.2 Dashboard and KPI Validation

- All numerical KPIs were confirmed to match aggregate query results from the MySQL database within a 15-minute refresh window.
- Material classification breakdowns (by EWC code and material type) were validated against manually verified test data sets.
- Reuse rate calculations were confirmed to correctly exclude materials in processing or quality assessment stages from the denominator.

6.2 Material Lifecycle Management Workflows Testing

6.2.1 Waste Production Event Architecture

- Correct assignment of European Waste Catalogue (EWC) codes from the complete EWC 2002 classification hierarchy, with validation against EWC code applicability rules.
- Linking of Waste Production Items (WPIs) to processing events, confirming material continuity through processing stages.
- Multi-material batch handling – confirmed correct disaggregation of mixed material batches into individual WPIs with appropriate EWC assignments.
- Quantity reconciliation – confirmed that sum of output WPI quantities did not exceed input WPI quantity for any processing event.

6.2.2 Attachment and Document Management

- CE Certificate upload and classification – confirmed correct storage and retrieval of CE Certificates linked to specific product records.

- Test report management – confirmed upload, versioning, and classification of laboratory test reports.
- Document access control – confirmed that attachment visibility was correctly restricted by user role and product ownership.
- Large file handling – tested upload and download of PDF documents up to 20 MB under field network conditions (simulated 3G, 4G, and broadband).

7. Challenges and Lessons Learned

7.1 Technical Implementation Challenges

- **Multi-System Interoperability with Legacy Infrastructure:** Integration testing revealed that certain construction management systems used by NIGRAD and partner organisations lacked modern REST API capabilities, requiring robust data transformation engines. The long-term sustainability of these adapters depends on legacy system upgrade roadmaps.

- **Offline Synchronisation Conflict Resolution:** In environments with intermittent network connectivity, the optimistic conflict resolution strategy encountered edge cases where concurrent modifications to the same material record from different devices required manual reconciliation. A conflict detection and notification system was implemented, alerting platform administrators to pending conflicts requiring review.

- **Gaia-X Clearing House API Versioning:** As documented in D2.3.5, the Gaia-X Clearing House APIs were subject to versioning changes during the project period. The integration layer was updated to support both v1 (production) and development environment APIs, with automated environment detection and fallback procedures.

- **IFC Export Compatibility:** IFC file import testing revealed minor schema compatibility issues between the platform's IFC 4 output and certain BIM authoring tools with incomplete standard coverage. Mitigation involved providing both IFC 2x3 (higher compatibility) and IFC 4 (richer data model) export options.

Maintaining tag readability during high-shear concrete mixing was a significant challenge, as standard ISO 15693 HF RFID tags failed. This was resolved using a dual-identification approach: UHF RFID tags prior to mixing, transitioning to QR code identification on finished panels. Additionally, parsing bulk aggregates into the CinderOSS API required adapting the logic to utilize 'width' and 'height' fields to capture nominal maximum fraction sizes mapped to a fixed 1,000 kg functional reference unit.

7.2 Operational and User Adoption Challenges

- **Digital Literacy Variability:** Varying levels of digital literacy among construction and waste processing operators at NIGRAD required investment in role-specific, hands-on training programmes during the early testing cycles. Training effectiveness was assessed through UAT task completion rates, which improved significantly between initial and final testing cycles.

- **Data Entry Consistency:** Initial testing cycles revealed inconsistencies in manual data entry, particularly for material quantity estimates at the point of demolition. Mitigation measures included standardised quantity estimation guidelines, dropdown menu standardisation for common material types, and mandatory field validation rules.

- **Stakeholder Engagement Across Partners:** Coordinating testing activities across geographically distributed partner organisations required intensive project management. Virtual testing sessions with shared screen access were introduced to enable partner participation beyond the NIGRAD physical site.

Visual quantity estimation by CDW demolition operators led to systematic underestimation. The platform was updated with explicit quantity verification steps at the weighbridge intake, configuring the DPP to display both the estimated origin quantities and verified processed quantities with explicit source attribution.

7.3 Regulatory and Compliance Challenges

- **Gaia-X Trust Framework Evolution:** The evolving nature of the Gaia-X Trust Framework specification required the testing environment to adapt schema and compliance parameters during the testing period. The modular architecture proved critical in enabling targeted updates without disrupting core platform functionality.

- **EU Digital Product Passport Regulatory Alignment:** The EU Digital Product Passport regulation continued to evolve during the project period, with sector-specific implementing acts for construction materials not yet finalised at the time of testing. The platform's DPP data model, developed with reference to the UN/CEFACT DPP 0.6.0 vocabulary, provides a forward-compatible foundation for alignment with final regulatory specifications.

- **Cross-Border Data Sovereignty:** Cross-border data sharing scenarios involving partners in Italy, Slovakia, and Slovenia required consultation with legal advisors to ensure GDPR compliance and compatibility with national data governance frameworks. The Gaia-X-based architecture provided a technically sound basis for these legal discussions.

7.4 Strategic Lessons Learned

- **Practical Demonstration Outperforms Abstract Explanation:** Experience at the NIGRAD pilot site confirmed that concrete, observable demonstrations – particularly the ability to scan an RFID tag and immediately view a signed DPP accessible to any external party – were far more effective in building stakeholder confidence than technical documentation or abstract descriptions of federated infrastructure.

- **Modular Architecture Enables Adaptation:** The modular four-tier architecture proved its value during the testing period by enabling targeted enhancements to specific platform components (Gaia-X integration, offline synchronisation, BIM export) without disrupting core material tracking operations.

- **Field-First Design is Essential:** Retrospective analysis of UAT results confirmed that operational ease in field conditions was the primary determinant of operator adoption.

Platform features with high administrative value but high field complexity were underutilised until simplified through UI redesign.

8. Conclusions and Next Steps

8.1 Summary of Testing Achievements

Deliverable 2.3.4 demonstrates that the digital solutions developed for circular construction within the ReBuilt project are technically functional, operationally validated, and capable of performing reliably in real-world construction and waste processing environments. The pilot testing conducted at the NIGRAD demonstration centre during Period 6 (M31–M36) has confirmed the platform's readiness for broader deployment across the Regional Circular and Digital Construction Hub network.

- End-to-end material traceability from demolition through processing to reuse, with cryptographically signed Digital Product Passports maintaining a verifiable chain of custody.
- Gaia-X-compliant federated identity infrastructure enabling trusted cross-border data sharing without centralised authority dependence.
- BIM interoperability through IFC-compliant data export, enabling incorporation of secondary material data into architectural and engineering workflows.
- CinderOSS marketplace integration facilitating matches between material producers and potential buyers, working towards the Grant Agreement target of ≥20 matches.
- Field-operable mobile application supporting RFID, NFC, and QR scanning with offline synchronisation capability.

The integration of CinderOSS, BIM, and GAIA-X infrastructure within a single coherent platform establishes a secure, cross-border digital value chain for circular construction materials without precedent in the Central European programme area.

8.2 Contribution to ReBuilt Objectives and Outputs

Table 8-1: D2.3.4 Contribution to ReBuilt Project Outputs

Output	Output Title	Contribution from D2.3.4
O2.2	Circular construction digital pilots	Primary validation deliverable confirming operational status of digital pilot at NIGRAD
O2.4	Digital solutions for circular construction	Confirms platform readiness for dissemination and replication across Hub network
O3.3	Regional Circular and Digital Construction Hubs	Provides technical baseline and deployment model for Hub digital infrastructure

The testing confirms that the digital platform significantly advances three of the project's core impact dimensions: it increases transparency of material flows through verifiable DPPs and full audit trails; it improves operational efficiency through automation of material documentation and marketplace listing workflows; and it supports regulatory compliance through Gaia-X-aligned data sovereignty architecture.

8.3 Next Steps and Recommendations

8.3.1 Immediate Next Steps (M36–M42)

- Finalise CinderOSS integration documentation and publish API integration guidelines for Regional Hub operators.
- Complete Gaia-X Clearing House connection in the production environment and establish automated credential renewal procedures as recommended in D2.3.5.
- Compile and publish the user training programme incorporating lessons learned from the NIGRAD UAT phase, with role-specific modules for field operators, coordinators, and administrators.
- **Scale-Up:** Initiate deployment at additional demonstration sites beyond NIGRAD, prioritising partner organisations in the Czech Republic (CZGBC), Slovakia (IIC), and Italy (INFORDATA commercial operations).

8.3.2 Medium-Term Development (M42–M60)

- Pursue alignment with the final EU Digital Product Passport implementing acts for construction materials as they are adopted, leveraging the existing UN/CEFACT DPP 0.6.0 and Gaia-X foundations.
- Develop enhanced analytics dashboards for Hub operators, providing aggregate insights on material flows, reuse rates, and marketplace activity across the Hub network.
- Explore blockchain integration for immutable provenance records as a complement to the existing Gaia-X signing infrastructure.

Planned expansions include: Month 31 - Onboard two additional agricultural partners to scale bio-concrete material supply. Month 32 - Expand the CDW tracking workflow to include wood waste streams (EWC 170201). Month 33 - Fully link multi-output CDW processing workflows, such as separating reinforcement steel from concrete.

8.3.3 Long-Term Vision

The long-term vision for the ReBuilt digital platform is EU-wide deployment as a reference implementation for Gaia-X-aligned circular construction data infrastructure. The modular architecture, open standards compliance, and practical validation at the NIGRAD demonstration centre collectively form a technology transfer asset supporting adoption across diverse Central European contexts. Integration with smart city infrastructure, urban material stock databases, and national CDW monitoring systems represents a strategic opportunity to extend the platform's impact from individual project-level tracking to regional and national circular economy policy implementation support.

References

- Interreg Central Europe 2021-2027 Programme. Grant Agreement CE0100390 – ReBuilt (Annex 1a). Version 2.0, 2023.
- INFORDATA SISTEMI SRL. ReBuilt Deliverable D2.3.1 – Testing the digital material passports and BIM interoperability. Period 5 (M25-M30). ReBuilt Project CE0100390.
- INFORDATA SISTEMI SRL. ReBuilt Deliverable D2.3.2 – Digital value chain and business ecosystem. Period 5 (M25-M30). ReBuilt Project CE0100390.
- INFORDATA SISTEMI SRL / Open Content. ReBuilt Deliverable D2.3.3 – Operating on-line digital marketplace for circular construction. Period 6 (M31-M36). ReBuilt Project CE0100390.
- INFORDATA SISTEMI SRL. ReBuilt Deliverable D2.3.5 – Development of GAIA-X use case. Version 2.0. Period 6 (M31-M36). ReBuilt Project CE0100390.
- European Commission. Ecodesign for Sustainable Products Regulation (EU) 2024/1781. Official Journal of the European Union. 2024.
- Gaia-X Association AISBL. Gaia-X Trust Framework. Version 22.10 and subsequent updates. 2022.
- W3C. Decentralized Identifiers (DIDs) v1.0. W3C Recommendation. 2022.
- W3C. Verifiable Credentials Data Model v1.1. W3C Recommendation. 2022.
- UN/CEFACT. Digital Product Passport Specification v0.6.0. 2023.
- buildingSMART International. IFC4 (ISO 16739-1:2018) Industry Foundation Classes. 2018.
- European Environment Agency. European Waste Catalogue (EWC) 2002/532/EC. 2002.

List of Acronyms

Acronym	Full Term	Context
BIM	Building Information Modelling	Digital 3D model-based process for construction
CDW	Construction and Demolition Waste	Waste generated by construction/demolition activities
DID	Decentralised Identifier	W3C standard for verifiable digital identity
DPP	Digital Product Passport	Digital record of a product's lifecycle and material data
ERDF	European Regional Development Fund	EU fund co-financing the Interreg programme

Acronym	Full Term	Context
EWC	European Waste Catalogue	EU standard waste classification system (2002/532/EC)
GAIA-X	European federated data infrastructure	EU initiative for data sovereignty in digital services
IFC	Industry Foundation Classes	Open BIM data exchange standard (ISO 16739)
NFC	Near Field Communication	Short-range wireless communication (ISO 14443)
NIGRAD	Nigrad komunalno podjetje d.o.o.	PP3 – demonstration centre operator, Maribor, SI
RBAC	Role-Based Access Control	Security model for permission management
RFID	Radio Frequency Identification	Wireless material tracking technology (ISO 15693)
SaaS	Software as a Service	Cloud-based software delivery model
UAT	User Acceptance Testing	End-user validation of system functionality
VC	Verifiable Credential	W3C standard for cryptographically signed credentials
WPI	Waste Production Item	Individual material item within a waste production batch