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D.2.3.1 Testing the digital material passports and BIM operability

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Executive Summary

Deliverable 2.3.1 presents the comprehensive digital solution developed by INFORDATA SISTEMI SRL within the ReBuilt project framework, addressing the construction sector's critical need for circular economy transformation. The construction industry currently accounts for 40% of EU energy consumption and generates over 35% of total waste, making digital material traceability solutions essential for achieving European sustainability goals.

Solution Overview and Technical Architecture

The implemented platform represents a significant advancement in construction material lifecycle management through a modular, cloud-based architecture built on the Yii2 PHP framework. The system integrates digital identification technologies including RFID, NFC, and QR codes to enable automatic material tracking throughout the construction value chain. The platform features a centralized MySQL database with RESTful API architecture, supporting real-time field data collection through mobile applications and comprehensive material status monitoring.

The solution demonstrates unprecedented interoperability through integration with Building Information Modelling (BIM) systems, Gaia-X federated infrastructure, and CinderOSS marketplace platforms. Digital Product Passports are generated using cryptographic signing with JsonWebSignature2020, ensuring data integrity and authenticity for downstream applications. The platform implements Gaia-X compliance through DID (Decentralised Identifier) using the did:web method and generates Verifiable Credentials through the official Gaia-X onboarding wizard for trusted organisational identity.

Real-World Implementation and Validation

The solution has been successfully deployed at the NIGRAD demonstration center, where it manages material flows from actual demolition and construction processes. The pilot demonstrates complete material lifecycle tracking from demolition through processing to reuse, with real-time inventory management incorporating geolocation and status monitoring capabilities. Materials are automatically classified using European Waste Catalogue codes, while transport, processing, and storage events maintain full audit trails for regulatory compliance.

The platform creates digital passports for materials with downloadable, machine-readable documentation in JSON-LD format, supporting seamless integration with third-party systems. Construction companies benefit from improved material inventory control and streamlined regulatory compliance, while waste management operators receive enhanced documentation and processing workflows. Material suppliers gain access to new markets through digital marketplace integration, and regulatory authorities benefit from automated reporting and transparent material flows.

Technical Innovation and Standards Compliance

The platform incorporates advanced security and trust infrastructure through cryptographic material authentication using eIDAS-aligned key generation and blockchain-ready architecture with optional distributed ledger integration. Role-Based Access Control (RBAC) provides granular permission management, while secure API endpoints with bearer token authentication enable safe third-party integration.

Data sovereignty requirements are addressed through full Gaia-X compliance, ensuring standardized metadata structures that support cross-border data discovery while maintaining European data protection standards. The flexible database schema accommodates diverse material types and processing workflows, while multi-language support includes English, Italian, and Slovenian with an extensible translation framework.

Impact and Scalability Potential

The digital pilot demonstrates measurable environmental and economic benefits across multiple dimensions. Environmental outcomes include reduced material waste through improved tracking and reuse identification, enhanced regulatory compliance reducing administrative burden, and transparent environmental impact tracking supporting sustainability reporting. Economic benefits encompass streamlined material management reducing operational costs, new revenue opportunities through digital marketplace access, and enhanced asset utilization through real-time inventory optimization.

The solution architecture supports broad scalability through its modular design enabling incremental functionality expansion and cloud-based infrastructure allowing elastic resource allocation. Standard API interfaces facilitate integration with existing construction software, while the technology-agnostic approach supports diverse hardware configurations. The flexible business model accommodates different organizational structures and includes compliance with emerging EU regulations on digital product passports and circular economy requirements.

Strategic Outlook and Recommendations

The successful implementation at NIGRAD provides a foundation for broader adoption across Central Europe and beyond. Immediate expansion opportunities include additional demonstration sites, integration with major BIM software platforms, and development of enhanced analytics dashboards for decision support. Medium-term development pathways focus on integration with emerging EU Digital Product Passport regulations, blockchain implementation for immutable material provenance records, and AI-powered material condition assessment capabilities.

The long-term vision encompasses EU-wide deployment supporting cross-border circular economy initiatives, integration with smart city infrastructure for urban material flows, and development of digital material exchanges creating liquid secondary markets. This approach positions stakeholders for compliance with evolving regulatory requirements while creating immediate operational value.

Conclusion

This deliverable demonstrates that comprehensive digital material traceability is technically feasible, economically viable, and environmentally essential for construction industry transformation. The INFORDATA SISTEMI solution provides a robust foundation for circular economy practices while offering immediate operational benefits and positioning stakeholders for future regulatory compliance. The successful integration of advanced technologies, including Gaia-X federated infrastructure, Digital Product Passports, and BIM compatibility, establishes this solution as a reference implementation for digital circular economy initiatives across Europe.

Through practical validation at the NIGRAD demonstration centre, the platform proves that digital technologies can bridge the gap between circular economy aspirations and operational reality, creating tangible value for all construction value chain stakeholders while advancing environmental sustainability objectives. The demonstrated interoperability and scalability provide confidence for replication and adaptation across diverse regional contexts, supporting broader EU sustainability and digital transformation goals.

1. Introduction

The European construction sector stands at a critical juncture in its evolution toward sustainability. Currently responsible for approximately 40% of the European Union's energy consumption, 36% of CO_2 emissions, and generating over 35% of total waste, the industry's traditional linear model of resource extraction, use, and disposal has reached its environmental and economic limits. The urgency for transformation has intensified with the European Green Deal's ambitious targets for climate neutrality by 2050 and the Circular Economy Action Plan's mandate for sustainable resource management across all sectors.

1.1. The Digital Transformation Imperative

Construction materials follow complex pathways through their lifecycle, often lacking comprehensive documentation that would enable effective reuse, recycling, or proper disposal. This information gap creates multiple inefficiencies: valuable materials are discarded rather than reused, regulatory compliance becomes administratively burdensome, and circular economy principles remain difficult to implement at scale. Digital technologies offer transformative potential to address these challenges by providing comprehensive material traceability, automated documentation, and data-driven decision support for circular practices.

The emergence of European digital infrastructure initiatives creates unprecedented opportunities for construction industry digitalization. Building Information Modelling (BIM) systems, which create digital representations of physical and functional building characteristics, are becoming standard practice in construction projects. Gaia-X represents Europe's approach to creating secure, federated data infrastructure that maintains data sovereignty while enabling cross-border collaboration. Digital Product Passports (DPP) are emerging as mandatory documentation requirements under EU regulations, providing comprehensive material documentation throughout product lifecycles. These technological foundations provide the essential building blocks for comprehensive circular economy solutions.

1.2. ReBuilt Project Context and Objectives

The ReBuilt project addresses these transformation challenges through collaborative development and demonstration of circular and digital solutions across the construction value chain. Funded under the European Union's research and innovation framework, ReBuilt brings together technology providers, construction companies, research institutions, and policy makers from Central European regions to create scalable solutions for material lifecycle management.

The project's approach combines technological innovation with real-world validation, ensuring that developed solutions address practical industry needs while remaining technically feasible and economically viable. Central to this strategy is the development of interoperable digital platforms that can integrate with existing construction workflows while supporting emerging regulatory requirements for material documentation and circular economy reporting.

ReBuilt builds upon previous European initiatives in construction digitalization and circular economy implementation, particularly leveraging lessons learned from the Retracking project which demonstrated the feasibility of RFID-based material tracking in construction environments. This foundation enables the development of more comprehensive solutions that address not only technical tracking capabilities but also integration with broader digital infrastructure and regulatory compliance requirements.

1.3. INFORDATA's Strategic Role and Expertise

INFORDATA contributes specialised expertise in automatic identification systems and digital tracking solutions to the ReBuilt consortium. The company's fifteen-year track record in RFID technology implementation, combined with experience in cloud-based platform development and system integration, positions it uniquely to address construction industry digitalisation challenges.

The company's portfolio includes extensive experience with supply chain tracking systems, inventory management platforms, and enterprise software integration across diverse industrial sectors. This background provides essential understanding of the operational challenges and technical requirements for implementing comprehensive material traceability systems in complex, multi-stakeholder environments such as construction projects.

INFORDATA's technical approach emphasises interoperability and scalability, recognising that successful digital transformation requires seamless integration with diverse existing systems and the flexibility to adapt to evolving regulatory requirements. This philosophy drives the development of modular, API-based architectures that can accommodate different organisational structures and technological configurations while maintaining consistent data quality and security standards.

1.4. Technical Innovation Framework

The digital solution presented in this deliverable incorporates several breakthrough technological implementations that advance the state of practice in construction material traceability. Digital Product Passports are generated using cryptographic signing techniques aligned with emerging EU regulations, ensuring data integrity and authenticity throughout material lifecycles. Integration with Gaia-X infrastructure demonstrates compliance with European data sovereignty requirements while enabling secure cross-border data sharing.

BIM compatibility ensures seamless incorporation into existing construction project workflows, allowing material tracking data to inform architectural and engineering decisions while maintaining consistency with industry-standard design and documentation practices. Marketplace connectivity through platforms such as CinderOSS provides practical channels for material reuse and circular economy implementation, creating economic incentives for sustainable practices.

The platform architecture incorporates modern web technologies including RESTful API design, cloud-based infrastructure, and mobile application interfaces that support real-time data collection and analysis. Role-Based Access Control (RBAC) systems ensure appropriate data security and privacy protection while enabling collaborative workflows across multiple organizations and stakeholder groups.

1.5. Deliverable

1.5.1 Scope and Innovation

This deliverable presents the complete digital pilot solution developed and implemented by INFORDATA SISTEMI within the ReBuilt project framework. The solution addresses critical gaps in construction material traceability through an integrated platform that supports material identification, lifecycle tracking, regulatory compliance, and circular economy decision-making.

The technical scope encompasses multiple integrated components: RFID and smart labelling systems for automatic material identification, mobile applications for field data collection, cloud-based management platforms for centralized data storage and analysis, and API-based integration capabilities for connection with external systems including BIM platforms, regulatory databases, and digital marketplaces.

The innovation extends beyond technical implementation to include comprehensive operational procedures, user training protocols, and performance measurement frameworks that enable practical deployment and

sustainable operation of the digital traceability system. This holistic approach ensures that technological capabilities translate into measurable improvements in material management efficiency, regulatory compliance, and circular economy outcomes.

1.6. Demonstration and Validation at NIGRAD Centre

The solution undergoes comprehensive validation at the NIGRAD demonstration centre in Slovenia, which serves as a controlled environment for testing circular construction practices with real materials and workflows. This facility processes materials from actual demolition and construction sites, providing authentic conditions for evaluating the platform's performance across diverse material types, processing requirements, and stakeholder interactions.

The NIGRAD pilot demonstrates the platform's capabilities in managing complete material lifecycles from initial demolition through classification, processing, storage, and eventual reuse or recycling. This real-world validation environment enables assessment of technical performance, user experience, integration effectiveness, and economic viability under operational conditions that reflect broader industry requirements.

The demonstration centre provides opportunities for stakeholder training and knowledge transfer, ensuring that developed solutions can be effectively implemented by construction companies, waste management operators, regulatory authorities, and other value chain participants. This practical validation approach strengthens the foundation for broader adoption and replication across different regional and organizational contexts.

1.7. Document Structure and Reader Guidance

This deliverable provides comprehensive documentation of the digital pilot solution. The document progresses from high-level system overview through detailed functional descriptions to comprehensive database schema documentation, concluding with lessons learned and strategic recommendations for broader adoption.

Technical implementers will find detailed architectural guidance, API specifications, and database schema documentation that support system replication and customization. Business stakeholders can focus on functional descriptions, integration capabilities, and economic impact assessments that inform adoption decisions. Policy makers will benefit from regulatory compliance approaches, data sovereignty implementations, and strategic recommendations for supporting circular economy transformation.

The documentation approach balances comprehensiveness with accessibility, providing sufficient technical detail for implementation while maintaining clarity for non-technical readers.

Through detailed examination of implementation challenges, integration successes, and operational outcomes, this deliverable contributes to the broader knowledge base supporting construction industry digital transformation and circular economy implementation across European markets. The lessons learned and best practices documented here provide valuable guidance for similar initiatives while demonstrating the practical viability of comprehensive digital material traceability solutions.

2 Basic Information about the Digital Solution

The digital solution developed by INFORDATA SISTEMI represents a comprehensive platform for material traceability and circular economy implementation in the construction sector. Built on modern web technologies and designed for scalability, the system addresses the fundamental challenge of tracking construction materials throughout their complete lifecycle while supporting integration with existing industry workflows and emerging regulatory requirements.

2.1 Solution Overview and Design Philosophy

The platform follows a modular architecture that separates concerns while maintaining seamless data flow between components. This design approach enables organizations to implement specific functionalities based on their immediate needs while preserving the ability to expand capabilities over time. The system supports multiple deployment models, from single-site implementations to federated networks spanning multiple organizations and geographical regions.

The technical foundation emphasizes interoperability and standards compliance, ensuring compatibility with existing construction industry tools including BIM systems, enterprise resource planning platforms, and regulatory reporting systems. Data sovereignty and security considerations are embedded throughout the architecture, with particular attention to European data protection requirements and Gaia-X compliance standards.

User experience design prioritizes practical usability in construction environments, recognizing that material tracking systems must function effectively under diverse field conditions with users having varying technical backgrounds. The interface design supports both desktop and mobile access patterns, with offline capability for field operations and automatic synchronization when connectivity is restored.

2.2 Core System Objectives

The digital solution addresses several interconnected objectives that collectively support circular economy transformation in construction:

Material Lifecycle Transparency enables complete traceability of construction materials and components from initial production or recovery through processing, storage, deployment, and end-of-life management. This transparency supports informed decision-making about material reuse, recycling, and disposal while providing the documentation necessary for regulatory compliance and environmental impact assessment.

Operational Efficiency Enhancement streamlines material management workflows through automated data capture, real-time inventory tracking, and integration with existing construction project management systems. These capabilities reduce administrative overhead while improving the accuracy of material documentation and status reporting.

Regulatory Compliance Automation supports emerging European Union requirements for Digital Product Passports, circular economy reporting, and waste management documentation. The system generates required documentation automatically while maintaining audit trails that demonstrate compliance with relevant regulations and standards.

Circular Economy Decision Support provides data-driven insights for identifying reuse opportunities, optimising material processing workflows, and connecting material suppliers with potential users through integrated marketplace functionality. These capabilities create economic incentives for circular practices while reducing environmental impact.

2.3 Architectural Components and Integration

The system architecture comprises four primary layers that work together to deliver comprehensive material traceability functionality:

Physical Interface Layer handles material identification and data capture through multiple technologies including RFID tags for automated scanning, QR codes for smartphone-based identification, and NFC tags for near-field communication applications. This multi-technology approach accommodates different operational requirements and technology preferences while ensuring consistent data capture across diverse usage scenarios.

Application Layer provides user interfaces and business logic implementation through web-based applications for comprehensive material management and mobile applications optimised for field data collection. The web platform supports administrative functions, reporting, and integration management, while mobile applications enable real-time material status updates, location tracking, and visual documentation capture.

Data Management Layer implements centralised storage and processing capabilities using MySQL database system with optimised schema design for material traceability requirements. This layer includes comprehensive backup and recovery procedures, performance optimisation for large-scale data operations, and security controls that protect sensitive information while enabling appropriate data sharing.

Integration Layer provides connectivity with external systems through RESTful API implementations that support both inbound and outbound data flows. Key integration capabilities include BIM system connectivity for architectural and engineering workflows, Gaia-X federation for secure cross-border data sharing, and marketplace platforms for material reuse promotion.

2.4 Digital Product Passport Implementation

Digital Product Passports represent a central innovation within the platform, providing comprehensive material documentation that travels with materials throughout their lifecycle. Each passport contains standardised metadata including material composition, processing history, environmental impact data, and technical specifications required for reuse assessment.

The passport generation process incorporates cryptographic signing using JsonWebSignature2020 algorithms, ensuring data integrity and authenticity verification by third-party systems. Passport data is structured using JSON-LD format for machine readability while supporting human-readable presentation through integrated viewing interfaces.

QR code integration enables direct access to passport information through mobile devices, supporting field verification and material assessment activities. The passport system supports versioning and update tracking, maintaining a complete history of material transformations while ensuring current information accuracy.

2.5 Technology Stack and Development Approach

The platform utilizes the Yii2 PHP framework for web application development, providing robust security features, efficient database integration, and modular architecture support. MySQL database systems handle data storage with optimized indexing for material tracking queries and reporting operations.

Development workflow incorporates Bitbucket for source code management and Jira for project tracking and collaboration. This approach supports agile development practices while maintaining code quality through version control and systematic testing procedures.

Cloud deployment architecture enables elastic scaling to accommodate varying usage patterns while providing geographic distribution for improved performance and data sovereignty compliance. The system supports both public cloud and private infrastructure deployment models based on organizational requirements.

2.6 Security and Compliance Framework

Security implementation follows industry best practices, including encrypted data transmission, secure authentication systems, and comprehensive activity logging for audit purposes. Role-Based Access Control (RBAC) enables granular permission management, ensuring users access only information and functions appropriate to their roles and responsibilities.

Gaia-X compliance implementation includes DID (Decentralised Identifier) generation using did:web methodology and Verifiable Credential creation through official Gaia-X onboarding procedures. These capabilities position the platform for participation in European federated data spaces while maintaining data sovereignty and security requirements.

Data protection measures address European GDPR requirements through privacy-by-design implementation, data minimisation practices, and user consent management capabilities. Backup and disaster recovery procedures ensure data availability while maintaining security during recovery operations.

3 Use Case Scenario

The digital material traceability platform operates within the complex ecosystem of construction material flows at the NIGRAD demonstration centre, supporting multiple stakeholder groups through integrated workflows that span the complete material lifecycle. This chapter presents detailed scenarios demonstrating how different users interact with the system to achieve their operational objectives while contributing to circular economy goals.

3.1 Stakeholder Ecosystem and Roles

The NIGRAD demonstration centre brings together diverse stakeholders who interact with the digital platform through different interfaces and for various purposes. Understanding these roles and their specific requirements provides essential context for evaluating system functionality and implementation success.

Demolition and Deconstruction Operators initiate material flows by documenting materials removed from buildings scheduled for demolition or renovation. These operators use mobile applications to capture initial material data including type, condition, quantity, and location, while attaching digital identifiers that enable subsequent tracking throughout the material lifecycle.

Waste Management Coordinators oversee material classification, processing, and storage operations at the NIGRAD facility. They use the web-based platform to manage incoming materials, assign processing workflows, track storage locations, and coordinate transportation to downstream users or processing facilities.

Construction Project Managers represent potential material users who access the platform to identify available materials for new construction or renovation projects. They evaluate material specifications, condition assessments, and availability timelines to make procurement decisions that incorporate circular economy principles.

Regulatory Compliance Officers utilize the system to generate required documentation for waste management reporting, environmental impact assessment, and circular economy performance measurement. They access comprehensive audit trails and automated reporting functions to demonstrate regulatory compliance.

Quality Assurance Technicians perform material condition assessments and testing, updating digital records with technical specifications, test results, and recommendations for appropriate reuse applications. Their input directly influences material classification and marketplace presentation.

3.2 Primary Use Case: Complete Material Lifecycle Management

This comprehensive scenario demonstrates the platform's core functionality through a typical material flow from demolition to reuse, illustrating how different stakeholders interact with the system at each lifecycle stage.

3.2.1 Material Origin and Initial Documentation

A demolition contractor arrives at a commercial building renovation project where concrete structural elements, steel reinforcement, and glazing systems require removal. Using the mobile application, the site supervisor begins material documentation by scanning QR codes pre-attached to significant building elements or by generating new digital identifiers for bulk materials.

For each identified material group, the operator enters basic information including material type selected from European Waste Catalogue classifications, estimated quantity using standard construction units, visual

condition assessment, and GPS coordinates for removal location. The mobile application captures photographic documentation automatically while prompting for additional details such as potential contamination concerns or special handling requirements.

The system generates a unique Waste Batch ID for each material group and creates initial Digital Product Passport entries that establish material provenance and begin the documentation trail. This information synchronises with the central platform immediately when internet connectivity is available or is stored locally for later upload in areas with limited coverage.

3.2.2 Transportation and Intake Processing

Upon material arrival at the NIGRAD facility, waste management coordinators use handheld scanners to identify incoming materials through their digital identifiers. The platform automatically updates material status to "received" and prompts for intake verification, including actual quantity measurement, condition reassessment, and storage location assignment.

Transportation events are documented through the platform's logistics module, capturing departure and arrival times, vehicle information, transport organization details, and any special handling requirements observed during transit. This information becomes part of the material's permanent record and supports regulatory reporting requirements for waste transportation documentation.

The system's integration with facility management tools enables automatic assignment of storage locations based on material type, processing requirements, and available space. Materials requiring immediate processing are flagged for priority handling, while stable materials are assigned to long-term storage areas with appropriate environmental controls.

3.2.3 Processing and Quality Assessment

Quality assurance technicians access detailed material records through the web platform to understand material history and previous condition assessments. They conduct standardised testing procedures appropriate to material type, entering results directly into the system through structured forms that capture technical specifications, performance characteristics, and recommended applications.

For concrete materials, testing might include compressive strength analysis, aggregate composition assessment, and contamination screening. Steel components undergo structural integrity evaluation, composition analysis, and surface condition assessment. The platform maintains standardised testing protocols for different material types while allowing customisation for specific quality requirements.

Processing workflows are managed through the platform's production module, which tracks materials through cleaning, sizing, sorting, and packaging operations. Each processing step updates the material's status and condition assessment while maintaining complete traceability of transformation activities. Processing equipment integration enables automatic capture of operational parameters such as crushing ratios, sorting criteria, and quality control measurements.

3.2.4 Marketplace Integration and Reuse Coordination

Processed materials ready for reuse are automatically listed on integrated marketplace platforms including CinderOSS, with Digital Product Passports providing comprehensive documentation for potential users. The marketplace integration includes material specifications, quality assessments, availability quantities, and location information necessary for procurement decision-making.

Construction project managers searching for materials can filter available inventory based on technical requirements, geographic proximity, delivery timelines, and environmental criteria. The platform's

recommendation engine suggests materials that meet project specifications while highlighting circular economy benefits such as embedded carbon reduction and waste diversion metrics.

When materials are selected for reuse, the platform manages the procurement workflow including availability confirmation, delivery coordination, and transfer documentation. Digital Product Passports are updated to reflect new ownership while maintaining complete historical records of material transformations and quality assessments.

3.3 Specialised Use Cases and Workflow Variations

The platform accommodates various specialised scenarios that demonstrate its flexibility and comprehensive functionality across different operational contexts.

3.3.1 Hazardous Material Management

Materials containing hazardous substances require specialised handling procedures that the platform supports through enhanced documentation and workflow controls. Hazardous material identification triggers additional data collection requirements including contaminant type and concentration, specialised testing protocols, and regulatory notification procedures.

The system maintains specialised compliance workflows for hazardous materials, automatically generating required documentation for regulatory authorities while restricting access to qualified personnel. Transportation and processing activities follow enhanced security protocols with additional approval requirements and monitoring procedures.

3.3.2 High-Value Component Recovery

Architectural elements and building systems with significant reuse value receive enhanced documentation and marketing support through the platform's premium component tracking capabilities. These materials undergo detailed condition assessment, professional photography, and comprehensive specification documentation that supports premium marketplace presentation.

The platform's integration with BIM systems enables creation of detailed component models that support architectural integration planning for reuse applications. Historical performance data and maintenance records enhance the value proposition for high-quality components while supporting warranty and performance expectations.

3.3.3 Bulk Material Processing

Large-quantity homogeneous materials such as concrete aggregate and crushed stone are managed through streamlined workflows optimised for efficiency while maintaining essential traceability requirements. Batch processing capabilities enable simultaneous handling of multiple material streams while preserving individual material identity and quality documentation.

Statistical quality control procedures sample representative portions of bulk materials for comprehensive testing while applying results to entire batches. This approach balances quality assurance requirements with operational efficiency for large-scale material processing operations.

3.4 Integration Workflows and External System Connectivity

The platform's integration capabilities enable seamless data exchange with external systems that support broader construction industry workflows and regulatory requirements.

3.4.1 BIM System Integration

Construction project teams using BIM software can access material availability data directly through integrated plugins that display available materials within design environments. Material selection within BIM systems triggers availability checks and procurement workflows while updating project sustainability metrics automatically.

The platform exports material data in IFC format for incorporation into building models, ensuring consistent documentation across design, procurement, and construction phases. This integration supports sustainable design decision-making while streamlining material specification and procurement processes.

3.4.2 Regulatory Reporting Automation

Monthly and annual regulatory reports are generated automatically using data collected throughout material processing workflows. The platform aggregates waste diversion metrics, material reuse percentages, and environmental impact reductions for submission to relevant authorities while maintaining detailed audit trails supporting compliance verification.

Integration with Gaia-X infrastructure enables secure data sharing with regulatory authorities while maintaining data sovereignty and privacy requirements. This capability supports emerging requirements for circular economy performance reporting while reducing administrative overhead for compliance activities.

3.5 Performance Measurement and Success Criteria

The NIGRAD demonstration enables measurement of concrete outcomes that validate the platform's effectiveness and support broader adoption planning.

Operational Efficiency Metrics include material processing time reductions, documentation accuracy improvements, and inventory management optimisation compared to traditional manual processes. These measurements demonstrate direct operational benefits that justify platform implementation costs.

Circular Economy Impact Metrics track material reuse percentages, waste diversion rates, and environmental impact reductions achieved through enhanced material tracking and marketplace connectivity. These outcomes support policy objectives while demonstrating economic and environmental benefits.

User Adoption and Satisfaction Metrics evaluate system usability, training effectiveness, and stakeholder satisfaction with platform functionality. User feedback drives continuous improvement while informing deployment strategies for broader implementation.

The comprehensive use case validation at NIGRAD provides empirical evidence supporting the platform's technical feasibility, operational effectiveness, and economic viability across diverse construction industry contexts.

4 System Architecture

The digital material traceability platform employs a layered, service-oriented architecture designed to support scalable, secure, and interoperable material tracking across diverse construction industry contexts. Built using modern web technologies and cloud-native principles, the architecture balances operational efficiency with regulatory compliance requirements while maintaining flexibility for future enhancements and integration capabilities.

4.1 Architectural Overview and Design Principles

The system architecture follows a four-tier design pattern that separates concerns while enabling seamless data flow and system integration. This approach supports independent scaling of different system components while maintaining data consistency and security across all operational layers.

Separation of Concerns ensures that data capture, business logic, data storage, and external integration functions operate independently while maintaining appropriate interfaces for coordination. This design pattern enables independent development, testing, and deployment of different system components while preserving overall system integrity.

API-First Design prioritises programmatic interfaces for all system functions, ensuring that web applications, mobile clients, and external integrations access identical functionality through consistent, well-documented interfaces. This approach supports multiple client implementations while maintaining centralised business logic and data management.

Security by Design integrates authentication, authorisation, and data protection measures throughout all architectural layers rather than treating security as an additional feature. Role-based access controls, encrypted communications, and comprehensive audit logging are embedded in core system functions.

Scalability and Performance considerations influence technology choices and architectural patterns throughout the system design. Stateless application components, optimised database schemas, and efficient caching strategies enable the platform to accommodate growing user bases and material volumes without fundamental architecture changes.

4.2 Architectural Layer Structure

The system implements a four-tier architecture that provides clear separation between user interfaces, business logic, data management, and external system integration while enabling efficient data flow and system coordination.

4.2.1 Presentation Layer

The presentation layer encompasses all user-facing interfaces, including web applications for comprehensive system management and mobile applications optimised for field operations. This layer focuses on user experience optimisation while maintaining consistent access to underlying system functionality.

Web Application Architecture utilises the Yii2 PHP framework's Model-View-Controller (MVC) pattern to separate user interface rendering from business logic implementation. Server-side rendering provides optimal performance for complex data displays while maintaining accessibility across diverse client environments. Responsive design principles ensure consistent functionality across desktop, tablet, and mobile web browsers.

Mobile Application Design prioritises offline capability and simplified workflows appropriate for field operations. Local data storage enables continued operation during network connectivity interruptions while

automatic synchronisation ensures data consistency when connectivity is restored. The mobile interface design emphasises large touch targets, minimal text input requirements, and visual workflow guidance appropriate for construction site environments.

User Interface Standardisation maintains consistent visual design and interaction patterns across all client applications while accommodating platform-specific user experience expectations. This approach reduces training requirements while ensuring familiar operation for users transitioning between different client interfaces.

4.2.2 Application Layer

The application layer implements core business logic including material tracking workflows, regulatory compliance procedures, and integration coordination functions. This layer contains the intelligence that transforms user inputs and external data into meaningful business outcomes while maintaining data integrity and security.

Business Logic Implementation utilizes Yii2's Active Record pattern for database interactions combined with service layer implementations that encapsulate complex business rules. This approach ensures consistent business logic application across different user interfaces while maintaining testability and maintainability of core system functions.

Workflow Management coordinates material lifecycle processes from initial identification through final disposition while maintaining appropriate approval workflows and quality checkpoints. State machine implementations track material status transitions while ensuring appropriate user permissions and data validation at each stage.

Integration Coordination manages data exchange with external systems through standardized interface implementations that abstract system-specific protocols and data formats. This approach enables consistent internal data handling while accommodating diverse external system requirements and communication protocols.

4.2.3 Data Management Layer

The data management layer provides persistent storage, data integrity enforcement, and performance optimisation for all system information while maintaining security and backup requirements appropriate for business-critical operations.

Database Design implements a normalised relational schema using MySQL that balances query performance with data integrity requirements. Comprehensive indexing strategies optimise common query patterns while foreign key constraints maintain referential integrity across complex material relationship structures.

Data Security Implementation includes field-level encryption for sensitive information, comprehensive access logging for audit requirements, and automated backup procedures that maintain data availability while preserving security controls. Database user accounts implement the principle of least privilege with application-specific credentials that limit access to required tables and operations.

Performance Optimization utilizes query optimisation techniques, strategic denormalisation for reporting functions, and caching implementations that reduce database load while maintaining data freshness requirements. Connection pooling and transaction management ensure efficient resource utilisation during peak usage periods.

4.2.4 Integration Layer

The integration layer manages all external system communications, including API implementations for third-party access, data synchronisation with partner systems, and compliance reporting to regulatory authorities while maintaining security and data sovereignty requirements.

RESTful API Implementation provides standardised interfaces for all system functions using JSON data formats and HTTP status codes that follow industry conventions. Comprehensive API documentation includes request/response examples, error handling procedures, and authentication requirements that support third-party integration development.

Security and Authentication utilise bearer token authentication for API access with role-based authorisation that restricts access to appropriate system functions based on user credentials and organisational relationships. Rate limiting and request monitoring prevent abuse while maintaining system availability for legitimate users.

External System Integration includes specialised connectors for BIM systems that support IFC data format exchange, Gaia-X federation protocols that enable secure cross-border data sharing, and marketplace platforms that facilitate material reuse coordination. Each integration maintains appropriate data transformation and error handling to ensure reliable operation despite external system variations.

4.3 Technology Stack and Implementation Details

The platform utilises proven open-source technologies that provide enterprise-grade reliability while maintaining cost-effectiveness and avoiding vendor lock-in concerns that could limit future flexibility.

4.3.1 Core Technology Components

Yii2 PHP Framework provides the foundation for web application development with built-in security features, efficient database abstraction, and comprehensive testing support. The framework's modular architecture supports clean separation of concerns while providing extensive libraries for common web application requirements.

MySQL Database System handles all persistent data storage with optimised configuration for material tracking query patterns and reporting requirements. InnoDB storage engine provides ACID compliance and row-level locking that supports concurrent operations while maintaining data integrity.

Apache/Nginx Web Server configurations provide high-performance request handling with SSL/TLS termination, static content optimisation, and load balancing capabilities that support horizontal scaling as system usage grows.

4.3.2 Development and Deployment Infrastructure

Version Control and Collaboration utilises Bitbucket Git repositories with branching strategies that support parallel development while maintaining code quality through pull request reviews and automated testing integration. Jira project management provides sprint planning, issue tracking, and team coordination capabilities.

Continuous Integration and Deployment implements automated testing pipelines that validate code changes before deployment while maintaining staging environments that mirror production configurations. Deployment automation reduces manual errors while supporting rapid response to security updates and feature requirements.

Monitoring and Operations includes application performance monitoring, error tracking, and resource utilisation analysis that support proactive system management and capacity planning. Log aggregation and analysis capabilities enable rapid troubleshooting while maintaining security and privacy requirements.

4.4 Security Architecture and Implementation

Security considerations are integrated throughout all architectural layers with particular attention to European data protection requirements and construction industry security expectations.

4.4.1 Authentication and Authorisation

Multi-Factor Authentication supports secure user access while accommodating field operation requirements where additional authentication factors may be impractical. Role-based access control implementation provides granular permission management that aligns with organisational structures and operational requirements.

API Security implements OAuth 2.0 patterns for third-party integrations while maintaining backward compatibility with simpler authentication methods for legacy system integration. Token management includes appropriate expiration policies and revocation capabilities that balance security with operational efficiency.

4.4.2 Data Protection and Privacy

Encryption Implementation includes TLS 1.3 for all network communications, AES-256 encryption for sensitive data at rest, and secure key management procedures that protect cryptographic materials while enabling legitimate access. Database encryption capabilities protect against unauthorised access while maintaining query performance.

Privacy by Design incorporates data minimisation principles, consent management capabilities, and data retention policies that comply with GDPR requirements while supporting legitimate business needs. User data export and deletion capabilities support individual privacy rights while maintaining audit trail requirements.

4.5 Scalability and Performance Considerations

The architecture accommodates growth in user base, material volume, and geographic distribution through horizontal scaling patterns and performance optimisation strategies.

4.5.1 Horizontal Scaling Design

Stateless Application Design enables multiple application server instances to handle user requests without coordination requirements while maintaining session consistency through external session storage. Load balancing distributes requests across available servers while providing automatic failover capabilities.

Database Scaling Strategies include read replica implementations for reporting workloads, connection pooling for efficient resource utilisation, and table partitioning strategies that maintain query performance as data volumes grow.

4.5.2 Performance Optimisation

Caching Implementation utilises Redis for session storage, query result caching, and frequently accessed data while maintaining cache invalidation strategies that ensure data freshness. Content delivery network integration optimises static resource delivery for geographically distributed users.

Query Optimisation includes strategic indexing, query plan analysis, and database schema optimisation that maintains response times as data volumes and complexity increase. Background processing for non-interactive operations prevents user interface delays while ensuring timely completion of system functions.

4.6 Disaster Recovery and Business Continuity

The architecture includes comprehensive backup, recovery, and business continuity capabilities that protect against data loss while ensuring rapid service restoration following system failures or security incidents.

Backup Strategy implements automated daily database backups with off-site storage, point-in-time recovery capabilities, and regular restore testing that validates backup integrity. Application code and configuration backups ensure complete system recovery capability.

High Availability Design includes redundant system components, automatic failover capabilities, and geographic distribution options that minimise service interruptions while maintaining data consistency and security requirements throughout recovery operations.

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

The digital material traceability platform achieves its strategic objectives through comprehensive integration with external systems that extend its functionality beyond isolated material tracking to encompass broader construction industry workflows, regulatory compliance frameworks, and circular economy ecosystems. This chapter details the technical implementation, operational procedures, and strategic value of these critical integrations.

5.1 Integration Architecture and Strategy

The platform's integration approach prioritises interoperability, security, and scalability while maintaining data sovereignty and regulatory compliance across diverse external system environments. Each integration is designed to provide bidirectional data exchange capabilities while preserving the integrity and performance of both internal platform operations and external system functions.

API-First Integration Design ensures that all external system connectivity utilises standardised RESTful interfaces with comprehensive authentication, authorisation, and monitoring capabilities. This approach enables consistent integration patterns while accommodating diverse external system architectures and communication protocols.

Data Sovereignty and Security considerations drive integration architecture decisions, particularly for cross-border data sharing and regulatory compliance systems. All integrations implement appropriate encryption, access controls, and audit logging while maintaining compliance with European data protection requirements and industry-specific security standards.

Scalability and performance optimisation ensures that external system integrations do not compromise platform performance while enabling efficient data synchronisation and real-time information exchange across multiple concurrent connections and varying external system response characteristics.

5.2 Building Information Modelling (BIM) Integration

BIM integration enables seamless incorporation of material tracking data into architectural and engineering workflows while supporting sustainable design decisions and construction project documentation requirements.

5.2.1 Technical Implementation

The BIM integration utilizes Industry Foundation Classes (IFC) data format compliance to ensure compatibility with major BIM software platforms including Autodesk Revit, Bentley MicroStation, and Graphisoft ArchiCAD. Material data export functions generate IFC-compliant datasets that include geometric properties, technical specifications, and material provenance information required for comprehensive building documentation.

Data Mapping and Transformation processes convert platform material records into IFC entity structures while preserving material tracking identifiers that enable bidirectional data synchronisation. Custom property sets extend standard IFC schemas to accommodate circular economy metadata including material lifecycle status, reuse potential assessments, and environmental impact calculations.

Real-Time Synchronisation capabilities enable BIM systems to access current material availability and specification data through API connections that support design decision-making while maintaining material reservation and procurement coordination functions within integrated project workflows.

5.2.2 Workflow Integration

Construction project teams utilise BIM integration to incorporate tracked materials directly into design models while accessing comprehensive material documentation including condition assessments, technical specifications, and Digital Product Passports. This integration supports sustainable design practices by providing immediate access to circular economy material options during design development phases.

Material Selection and Specification workflows enable architects and engineers to identify available materials that meet project requirements while accessing detailed condition assessments, technical testing results, and compatibility information necessary for specification decisions. Integration with project scheduling systems coordinates material availability with construction timelines.

Sustainability Reporting functions automatically calculate project-level circular economy metrics including material reuse percentages, embodied carbon reductions, and waste diversion achievements based on material selections documented within BIM models. These calculations support green building certification requirements and environmental impact reporting.

5.2.3 Implementation Status and Capabilities

Current BIM integration provides IFC export functionality that enables material data incorporation into external BIM systems while maintaining material tracking identifiers for ongoing project coordination. Download capabilities generate IFC files containing material geometry, properties, and documentation links that support comprehensive building information management.

Future development roadmap includes bidirectional synchronisation capabilities that will enable BIM systems to update material status and trigger procurement workflows directly from design environments. API-based real-time integration will provide live material availability data within BIM software interfaces while supporting automated sustainability calculations.

5.3 Gaia-X Federated Infrastructure Integration

Gaia-X integration positions the platform within European federated data infrastructure while ensuring data sovereignty, security, and interoperability across construction industry digital ecosystems.

5.3.1 Identity and Trust Infrastructure

The platform implements Gaia-X identity standards through Decentralised Identifier (DID) architecture using the did:web method that establishes verifiable organisational identity within federated networks. DID document publication at https://rebuilt.way.to.it/.well-known/did.json provides public access to cryptographic verification materials while maintaining secure private key management.

Verifiable Credentials generated through official Gaia-X onboarding procedures establish trusted organisational identity that enables secure data sharing across federated networks. Credential verification processes ensure authentic participant identification while supporting automated trust establishment for cross-border collaborations. To establish trusted organisational identity within Gaia-X, Participant Verifiable Credentials were created using the official Gaia-X onboarding wizard as shown in Table 1:

Cryptographic Security implementation utilises eIDAS-compliant key generation and JsonWebSignature2020 signing algorithms that ensure data integrity and authenticity verification for all federated data exchanges.

Private key protection and certificate management procedures maintain security while enabling automated verification processes.

5.3.2 Data Federation and Sharing

Gaia-X compliance enables secure material data sharing across European construction networks while maintaining data sovereignty and privacy requirements. Federated query capabilities allow authorised participants to discover available materials and services without exposing sensitive organisational information or compromising competitive advantages.

Metadata Standardisation follows Gaia-X ontology requirements that ensure consistent data discovery and interoperability across diverse organisational systems and national jurisdictions. Material data publishing includes appropriate classification, access controls, and usage policies that protect intellectual property while enabling circular economy collaboration.

Cross-Border Compliance implementation addresses varying national regulations and data protection requirements while maintaining seamless data access for authorised participants. Legal framework documentation and terms of service agreements ensure regulatory compliance while enabling practical data sharing operations.

5.3.3 Operational Implementation

Current Gaia-X integration provides foundational identity and verification infrastructure that establishes platform trustworthiness within federated networks. DID implementation and Verifiable Credential generation enable participation in Gaia-X ecosystems while maintaining operational independence and data control.

The platform publishes material availability metadata through Gaia-X-compliant interfaces that enable discovery by authorised participants while maintaining appropriate access controls and pricing information. Integration with Gaia-X clearing houses provides automated compliance verification and participant validation for secure collaboration.

Table 1: Gaia-X DID and Verifiable Credential Configuration

Parameter	Value	Description
DID Method	did:web	Gaia-X-compliant method for decentralised identifiers
DID	did:web:rebuilt.way.to.it	Root DID representing the platform
Verification Method	did:web:rebuilt.way.to.it#key-1	Reference to public key fragment inside the DID document
DID Document Location	https://rebuilt.way.to.it/.well-known/did.json	Publicly accessible DID document
Issuer	https://rebuilt.way.to.it	Platform base URL used as issuer identifier in the VC
Verifiable Credential ID	https://rebuilt.way.to.it/.well-known/participant.json	URL under which the VC is published
Credential Subject ID	https://rebuilt.way.to.it/.well-known/participant.json#subject	Subject identifier embedded in the VC

Parameter	Value	Description
Terms and Conditions URL	https://rebuilt.way.to.it/.well-known/gx-terms-and-cs.json	JSON document defining legal terms and Gaia-X conditions
Terms and Conditions Subject ID	https://rebuilt.way.to.it/.well-known/gx-terms-and-cs.json#subject	Identifier inside the terms document
VC Creation Method	wizard.lab.gaia-x.eu / API endpoint	Used for generating and validating VCs
Gaia-X Environment	Clearing Houses v1 (production) / Gaia-X dev	Depending on target environment: production or test

5.4 CinderOSS Marketplace Integration

CinderOSS integration provides access to transnational circular economy networks that facilitate material reuse and knowledge sharing across Central European construction markets.

5.4.1 Material Marketplace Functions

Processed materials with confirmed quality certification are made discoverable through CinderOSS via the publication workflow operated by Open Content (PP4), with comprehensive material documentation including Digital Product Passport references, condition assessments, and technical specifications. Marketplace listings include availability quantities, location information, and contact details necessary for procurement coordination. The full marketplace operating model and curation workflow are documented in D.2.3.3.

Listing Management is curator-supported. Changes in the traceability platform are reflected in CinderOSS listings through scheduled publication or operator-initiated update, with the choice of mechanism depending on the type of update and on the volume of material records being managed at any given time. Substantive changes to factual content go through full review; minor changes (typography, broken links, formatting) can be applied by the operator without re-review.

Search and Discovery optimisation ensures that platform materials appear prominently in relevant marketplace searches while maintaining competitive positioning and accurate specification matching. Enhanced material documentation and professional photography improve marketplace presentation and buyer confidence.

5.4.2 Knowledge and Technology Sharing

CinderOSS integration extends beyond material marketplace functions to include sharing of processing technologies, best practices, and regulatory compliance approaches that support broader circular economy adoption across construction industry networks.

Technology Catalogue Publishing enables sharing of successful material processing techniques, quality assessment procedures, and digital tracking implementations that support knowledge transfer and capability development across marketplace participants.

Regulatory Framework Integration provides access to evolving End-of-Waste criteria, circular economy legislation, and compliance procedures that support consistent regulatory interpretation and implementation across diverse jurisdictional requirements.

5.4.3 Implementation Results and Performance

CinderOSS integration has successfully facilitated material transactions across regional boundaries while maintaining comprehensive documentation and quality assurance standards. Digital Product Passport sharing through marketplace interfaces has improved buyer confidence and transaction completion rates.

Performance metrics demonstrate increased material utilization rates and expanded geographic reach for processed materials while maintaining quality standards and regulatory compliance requirements. Integration monitoring provides insights into marketplace effectiveness and optimization opportunities.

CinderOSS itself is operated by Open Content (PP4) as a separately registered Gaia-X Legal Participant under the cinderela2 continuity framework, with did:web:opencontent.it as its identifier and a public Digital Product Passport endpoint at https://cindeross.cinderela.eu/api/dpp. The CinderOSS Gaia-X registration is described in D.2.3.5 section 5.3 and in D.2.3.3 section 2.4. The ReBuilt context therefore contains two complementary Gaia-X Legal Participants along the same value chain.

5.5 Digital Product Passport Implementation and Standards

Digital Product Passport functionality represents a critical integration component that ensures compliance with emerging EU regulations while providing comprehensive material documentation throughout lifecycle management.

5.5.1 Technical Standards and Compliance

DPP generation utilises JSON-LD data format structured according to schema.org specifications that ensure machine readability and interoperability across diverse software systems and regulatory frameworks. Cryptographic signing using JsonWebSignature2020 provides data integrity verification and authenticity confirmation for downstream users.

Regulatory Alignment ensures DPP content matches emerging EU requirements for product transparency, circularity assessment, and environmental impact documentation. Standardised metadata fields support automated compliance verification while accommodating evolving regulatory specifications.

Blockchain Readiness architecture enables future integration with distributed ledger systems while maintaining current operational efficiency through traditional database storage. Hash generation and signature verification provide immediate authenticity confirmation without requiring blockchain infrastructure.

5.5.2 User Interface and Access Methods

DPP access through integrated web interfaces provides comprehensive material documentation including embedded viewers for inline content display and download capabilities for machine-readable formats. QR code generation enables direct mobile access to material passports while supporting field verification and assessment activities.

Multi-Format Support accommodates diverse user requirements through human-readable web presentations, machine-readable JSON-LD downloads, and API access for automated system integration. Format selection optimizes information presentation for specific use cases while maintaining content consistency.

Version Management tracks DPP updates and modifications while maintaining historical records of material transformations and documentation changes. Audit trails support regulatory compliance and quality assurance requirements while enabling material lifecycle analysis.

Figure 1 shows a product page that displays detailed information about the product and provides access to its Digital Product Passport (DPP) in JSON-LD format.

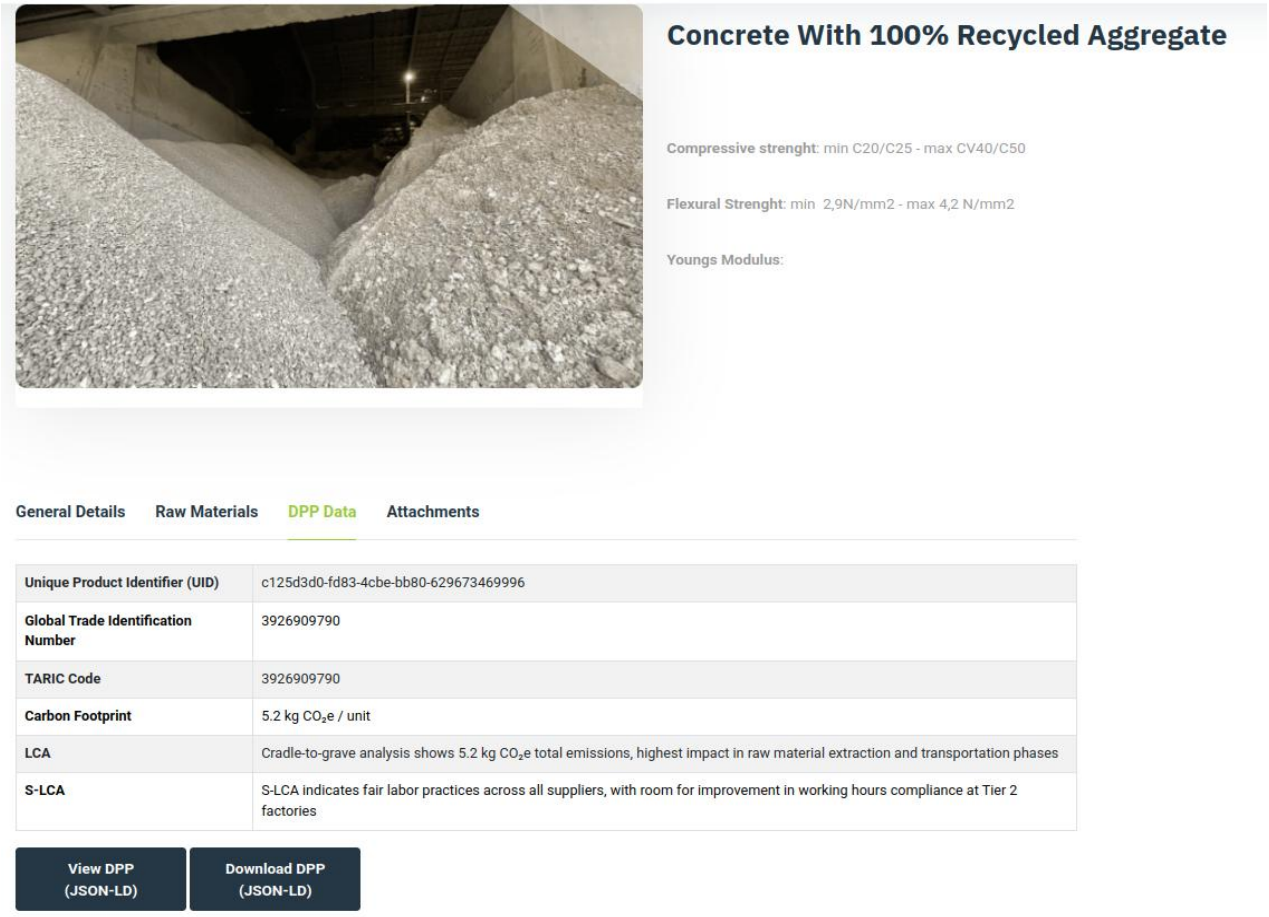

Figure 1: Product details page with DPP data (ReBuilt portal screenshot)

5.5.3 Integration with External Systems

DPP data sharing through external system APIs enables incorporation into procurement systems, quality management platforms, and regulatory reporting tools while maintaining appropriate access controls and intellectual property protection.

API-Based Access provides programmatic interfaces for third-party systems requiring material documentation while implementing authentication and authorisation controls that protect sensitive information. Rate limiting and monitoring ensure system availability while preventing unauthorised access or data harvesting.

Regulatory Reporting Integration enables automated submission of DPP data to compliance systems while maintaining audit trails and verification procedures required for regulatory acceptance. Integration with emerging EU digital infrastructure supports seamless compliance with evolving requirements.

5.6 Integration Monitoring and Performance Management

Comprehensive monitoring and performance management ensure reliable operation of all external system integrations while providing insights for optimisation and capacity planning.

5.6.1 Performance Monitoring and Optimisation

Integration performance monitoring tracks response times, success rates, and error conditions for all external system connections while providing automated alerting for service disruptions or performance degradation. Performance metrics inform capacity planning and optimisation decisions while ensuring a consistent user experience.

Error Handling and Recovery procedures provide graceful degradation during external system outages while maintaining platform functionality through cached data and offline operation modes. Automatic retry mechanisms and exponential backoff strategies optimise recovery performance while preventing system overload.

Capacity Planning analysis predicts integration scaling requirements based on usage patterns, data volumes, and external system performance characteristics. Proactive scaling ensures adequate capacity while optimising resource utilisation and cost management.

5.6.2 Security and Compliance Monitoring

Security monitoring for all external integrations includes authentication verification, data transmission encryption, and access pattern analysis that identifies potential security threats or compliance violations. Automated alerting enables rapid response to security incidents while maintaining comprehensive audit trails.

Compliance Verification procedures ensure ongoing adherence to data protection requirements, industry standards, and regulatory obligations across all external system integrations. Regular compliance assessments identify potential issues while supporting certification and audit requirements.

Data Governance implementation maintains appropriate data classification, retention policies, and access controls for information shared through external system integrations. Privacy protection measures ensure compliance with GDPR and industry-specific requirements while enabling legitimate business operations.

6 Platform Functionalities

The digital material traceability platform provides comprehensive functionality for managing construction material lifecycles through intuitive web-based interfaces that accommodate diverse user roles and operational requirements. This chapter presents the platform's core functional modules, demonstrating how different stakeholder groups utilise system capabilities to achieve material tracking, regulatory compliance, and circular economy objectives.

6.1 Platform Overview and User Experience Design

The platform implements a role-based interface design that presents relevant functionality to each user type while maintaining consistent navigation and interaction patterns across all modules. Dashboard customisation enables users to access frequently used functions efficiently while providing comprehensive functionality through organised menu structures.

Responsive Design Implementation ensures consistent functionality across desktop, tablet, and mobile devices while optimising interface layouts for different screen sizes and interaction methods. Touch-friendly controls and simplified mobile workflows accommodate field operations while maintaining access to comprehensive functionality when detailed analysis is required.

User Experience Optimization prioritizes task completion efficiency through streamlined workflows, contextual help systems, and intelligent defaults that reduce data entry requirements while maintaining data quality and completeness. Progressive disclosure techniques present basic functionality prominently while providing access to advanced features when needed.

Figure 2 shows the dashboard that appears when the portal is loaded.

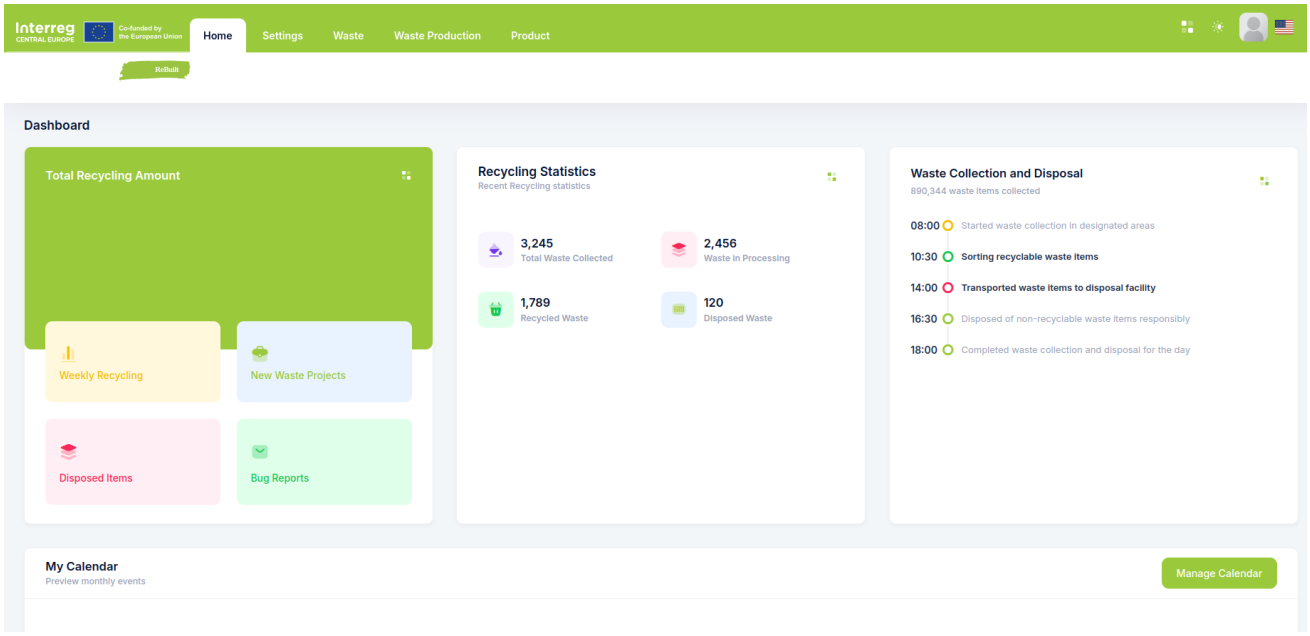

Figure 2: Start page (ReBuilt portal screenshot)

6.2 Material Lifecycle Management Workflows

The platform's core functionality centres on comprehensive material tracking capabilities that support complete lifecycle management from initial identification through final disposition while maintaining regulatory compliance and quality assurance standards.

6.2.1 Waste Production and Material Intake

Material lifecycle management begins with waste production documentation that captures materials removed from demolition or construction sites. The waste production module provides structured data entry forms that accommodate varying material types, quantities, and handling requirements while maintaining consistency with European Waste Catalogue classifications.

Figure 3 illustrates The Waste menu, which includes 2 sub-menus: Waste Type and Waste Type Categories.

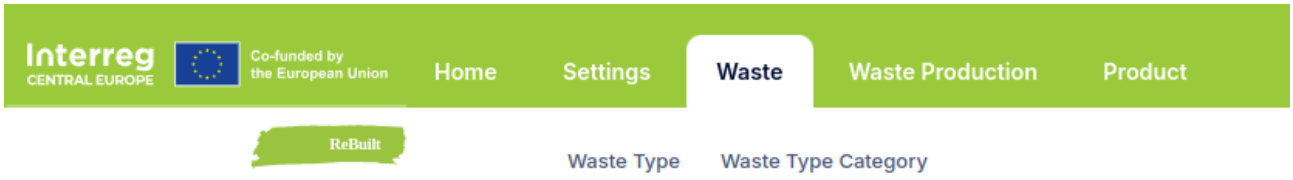

Figure 3: Waste menu (ReBuilt portal screenshot)

Waste Production Creation enables users to document material sources including demolition locations, material types, estimated quantities, and responsible organisations. The system generates unique disposal numbers and batch identifiers that maintain material traceability throughout subsequent processing stages while supporting regulatory reporting requirements.

Material Item Documentation allows detailed specification of individual material types within broader waste production records. Users can specify precise quantities, units of measurement, material conditions, and special handling requirements while attaching supporting documentation such as photographs, test results, and safety data sheets.

The **Waste Type** index section contains a grid with the list of waste types. Figure 4 illustrates the Waste Types list.

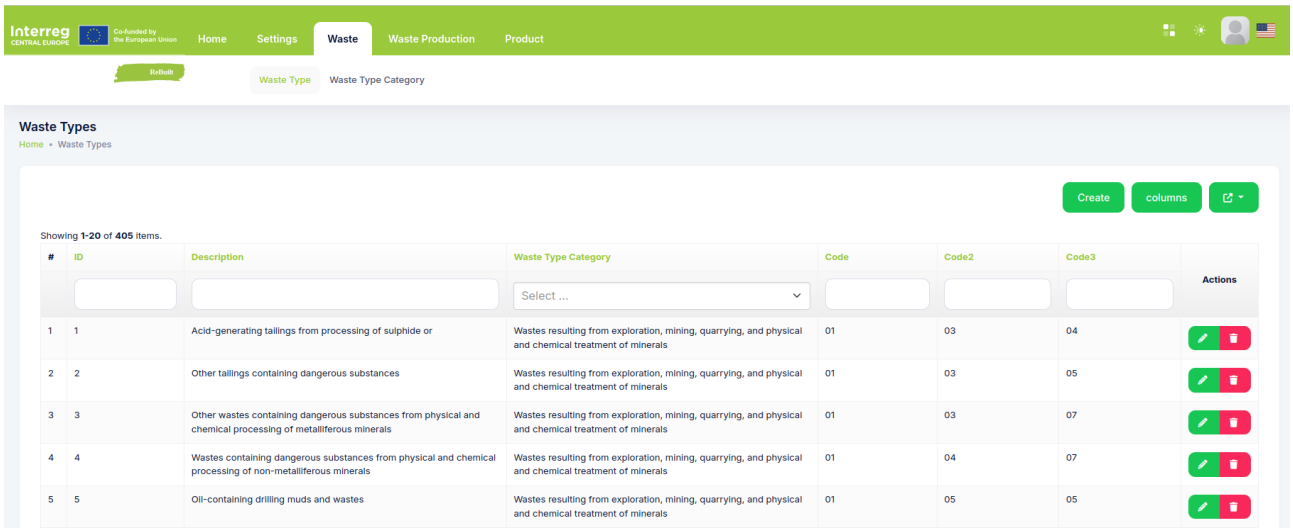

Figure 4: Waste types list (ReBuilt portal screenshot)

Dedicated action buttons are available in the Index section, as shown in Table 2.

Table 2: Action buttons in Waste Type Index section

Create	Function that creates a new Waste Type element
columns	Tool to manage columns to visualise in view grid. Allow to customise grid view
HTML CSV Text PDF Excel 95 + Excel 2007+	Tool to save information from grid to file in different formats

By clicking on the pencil icon ( ), the waste type linked to specific events can be visualised and managed. Figure 5 shows details of Waste Type.

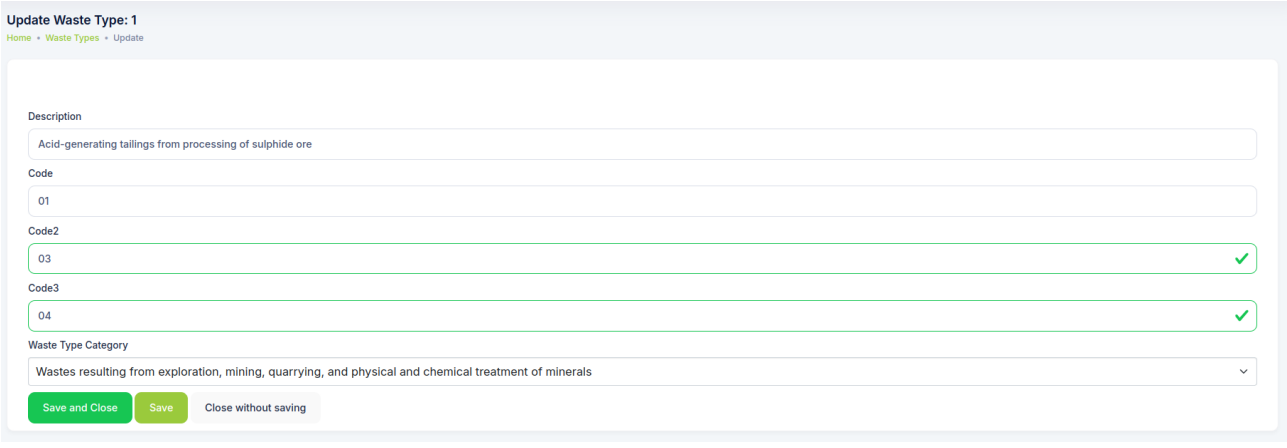

Figure 5: Details Waste Type (ReBuilt portal screenshot)

Figure 6 shows the **Waste Type Categories** index section, which contains a grid listing the waste type categories.

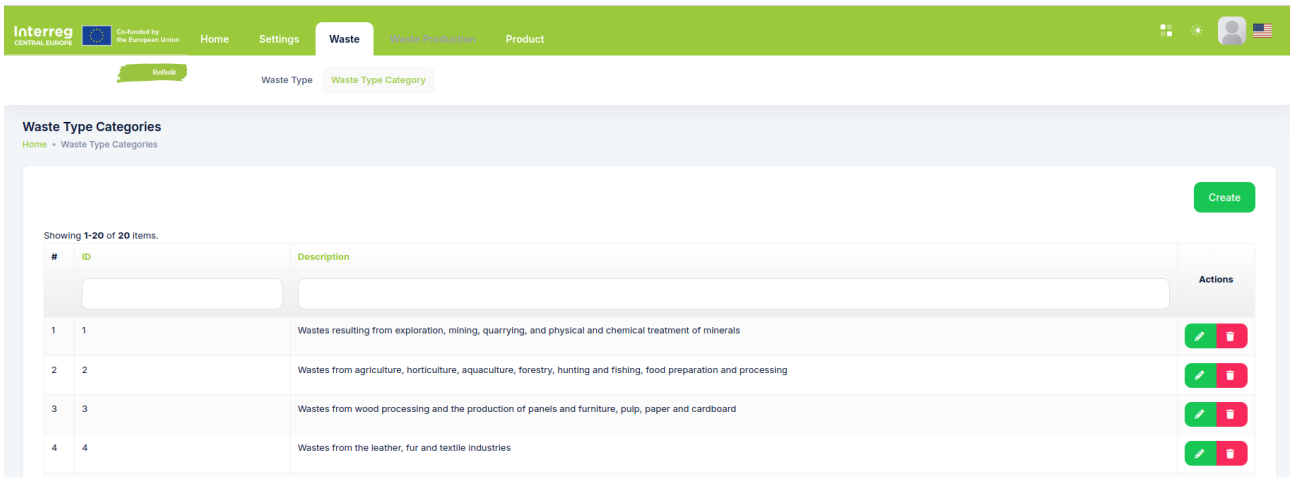

Figure 6: Waste Type Categories list (ReBuilt portal screenshot)

Dedicated action buttons are available in the Index section, as shown in Table 3.

Table 3: Action button in Waste Type Categories Index section

Create	Function that creates a new Waste Type Category element

By clicking on the pencil icon ( ), the waste type category linked to specific events can be visualised and managed. Figure 7 illustrates the form used to create a Waste Type Category.

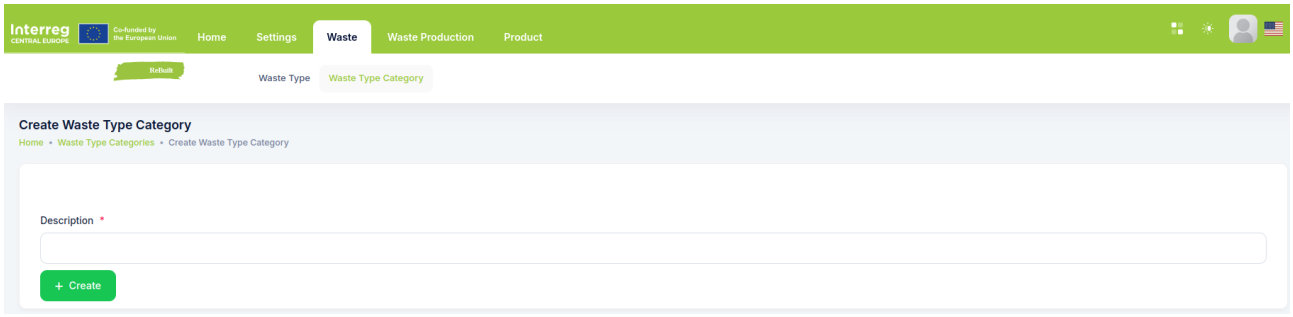

Figure 7: Create Waste Type Category (ReBuilt portal screenshot)

Menu **Waste Production** contains 1 sub-menu **Waste Production**. Figure 8 illustrates menu **Waste Production**.

Figure 8: Waste Production menu (ReBuilt portal screenshot)

Figure 9 shows the **Waste Production** index section contains a grid with the list of waste production.

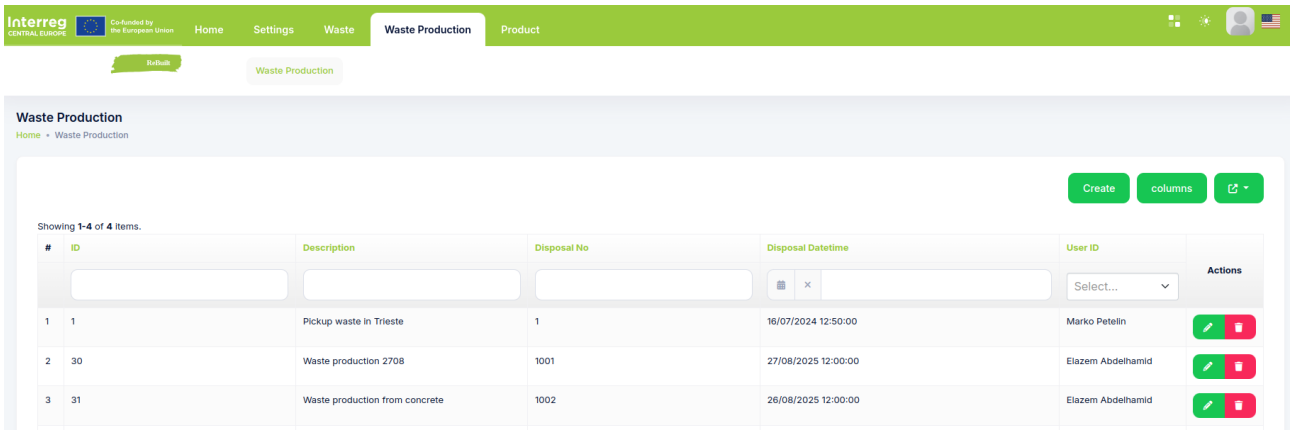

Figure 9: Waste Production list (ReBuilt portal screenshot)

Dedicated action buttons are available in the Index section. Table 4 lists the buttons that can be used in this section.

Table 4: Action button in Waste Production Index section

Create	Function that creates a new Waste Production element
columns	Tool to manage columns to visualise in the view grid. Allow to customise grid view
HTML CSV Text PDF Excel 95 + Excel 2007+	Tool to save information from grid to file in different formats

Here you can see all your waste productions listed. You can create new records, edit existing ones, or open them to view full details. Waste Productions are the starting point in the form.

Main functionality:

Work with Production Items (WPIs)

Each Waste Production can include several Production Items. From a Waste Production, you can navigate into its Production Items. Here you can record the type of waste, its quantity, unit, and batch ID. You can also attach photos or documents to keep everything in one place.

Track Waste Production Events (WPEs)

From a Production Item, you can further navigate into its related Events. For each disposal item, you can log events such as transport, processing, or storage. Events include important details like arrival and departure times, locations, organisations, and permits. Each event shows a clear status (e.g., recorded, in transit, processing) so you always know what's happening.

Clicking on the pencil icon opens the detailed Waste Production form. For user convenience, a Back button is available on each level, allowing you to return one step back (from Events to Production Items, or from Production Items to Waste Productions).

Figure 10 shows the details of a Waste Production record. The left side shows general information about Waste Production (description, disposal datetime, disposal number, supplier and demolishing organisation name, etc.). On the right side - list of Waste Production Items (WPI) that are specified for a particular Waste Production.

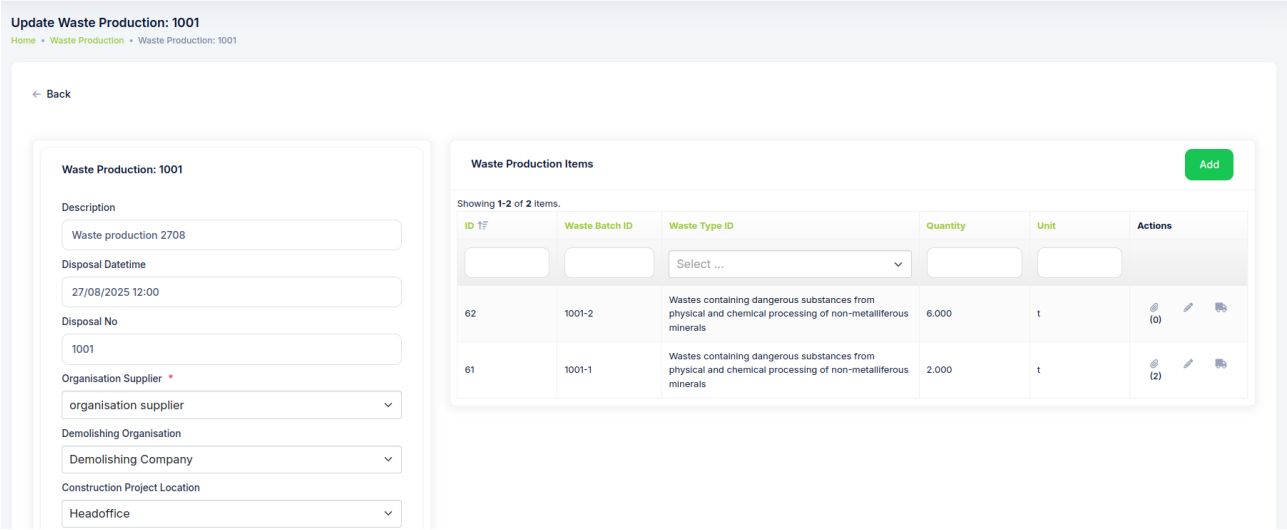

Figure 10: Details Waste Production. (ReBuilt portal screenshot)

Each WPI shows its Waste Batch ID, quantity, unit, waste type, etc. In Action, columns show buttons: attachments, edit WPI, create transport event.

By clicking the attachment preview button (2), you can view and manage the files attached to the WPI, as shown on Figure 11.

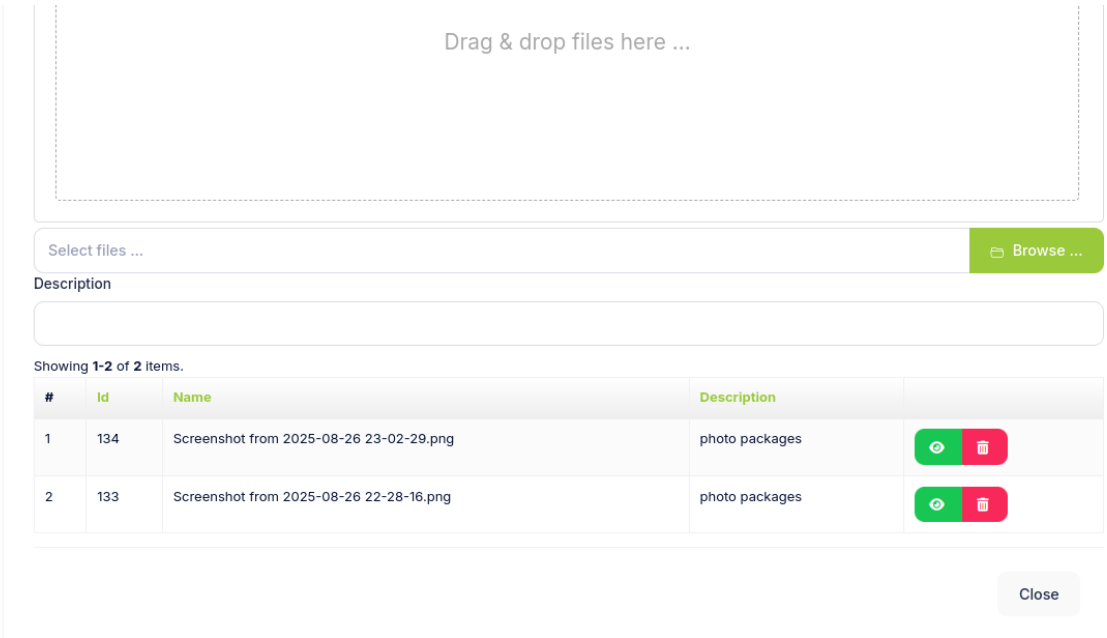

Figure 11: Waste Production Item Attachments (ReBuilt portal screenshot)

Figure 12 shows the pop-up window for adding a new WPI, opened by clicking the Add button.

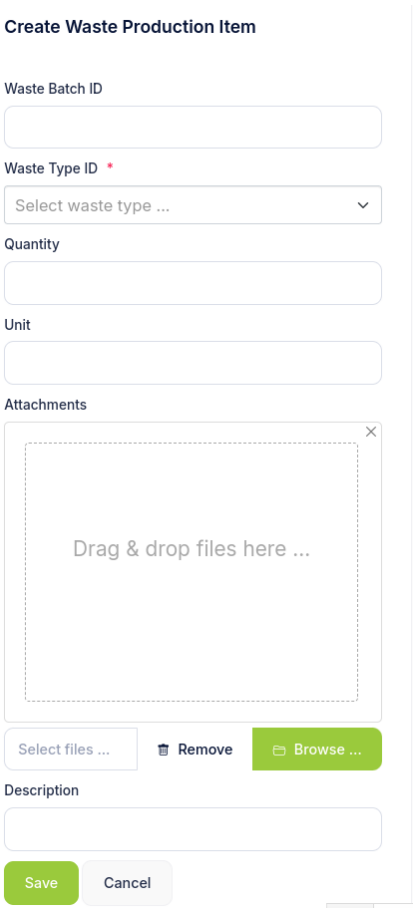

Figure 12: Create Waste Production Item. (ReBuilt portal screenshot)

Figure 13 shows the details of the Waste Production Items (WPI) record. On the left side shows general information about WPI properties (quantity, unit, type, batch ID). On the right side - list of all events linked to this WPI. A WPE represents an event in the lifecycle of a WPI (e.g., transport, processing, treatment).

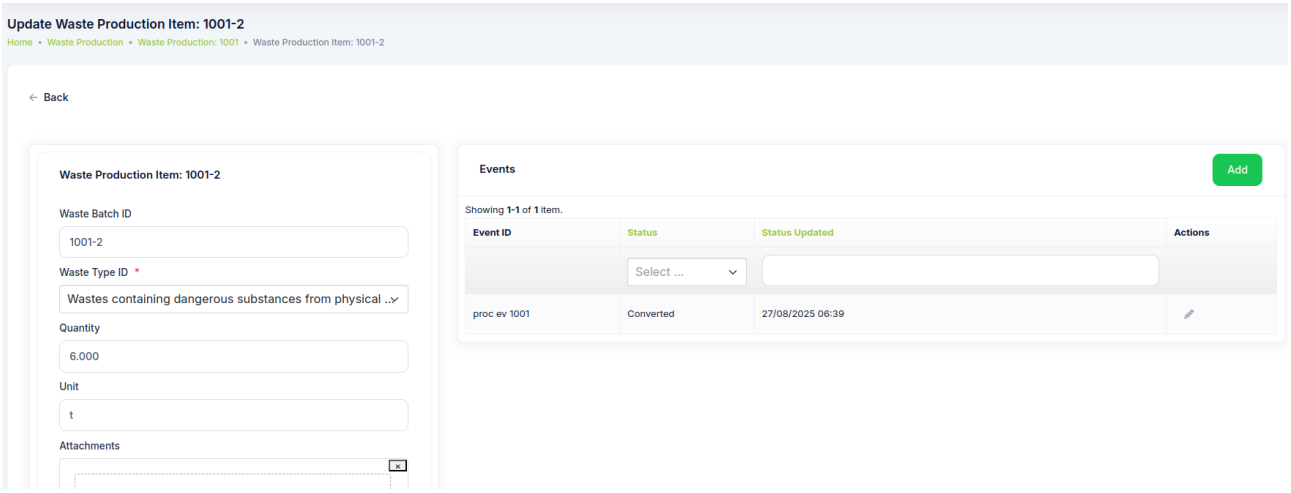

Figure 13: Edit Waste Production Item. (ReBuilt portal screenshot)

Click on Edit button or Add button open WPE form, as shown in Figure 14. The screen is divided into several expandable sections (accordions) for better organization. On the top display current status and Extra info: Free-text notes entered by the operator

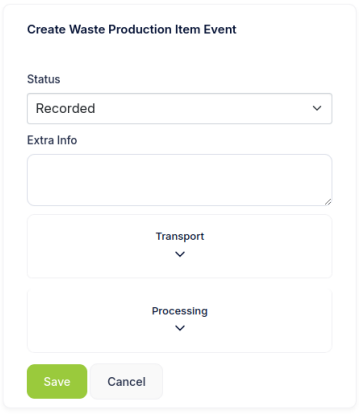

Figure 14: Form Waste Production Item Event. (ReBuilt portal screenshot)

Transportation Event Tracking captures material movement from source locations to processing facilities while documenting transportation organisations, vehicle information, departure and arrival times, and any special handling requirements observed during transit. This information supports regulatory compliance and provides complete audit trails for material provenance verification.

Figure 15 illustrates the fields associated with transport events.

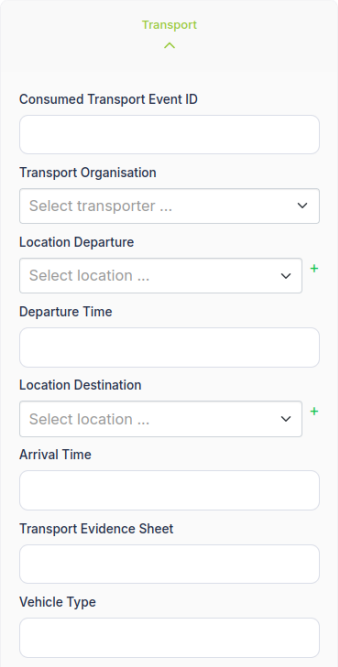

Figure 15: Form Waste Production Item Event. Transport Section (ReBuilt portal screenshot)

Displays next fields:

- Consumed Transport Event ID
- Arrival → Arrival date & time.
- Departure → Departure date & time (if available).
- Departure Location → Select the location from which the waste was departed
- Destination Location → Select the location to which the waste is transported.
- Vehicle Type → Type of transport used (e.g., truck, ship).
- Transport Evidence Sheet → Reference or code for documentation.
- Transport Organisation → The organization responsible for transport.

If there is no Location in the Directory of Locations, you can add a new one by clicking "+" near the location field. As shown in Figure 16, you can add a new location by selecting it on the map or by searching for it using the address field. The address field has an autocomplete feature to make it easier to find the correct address.

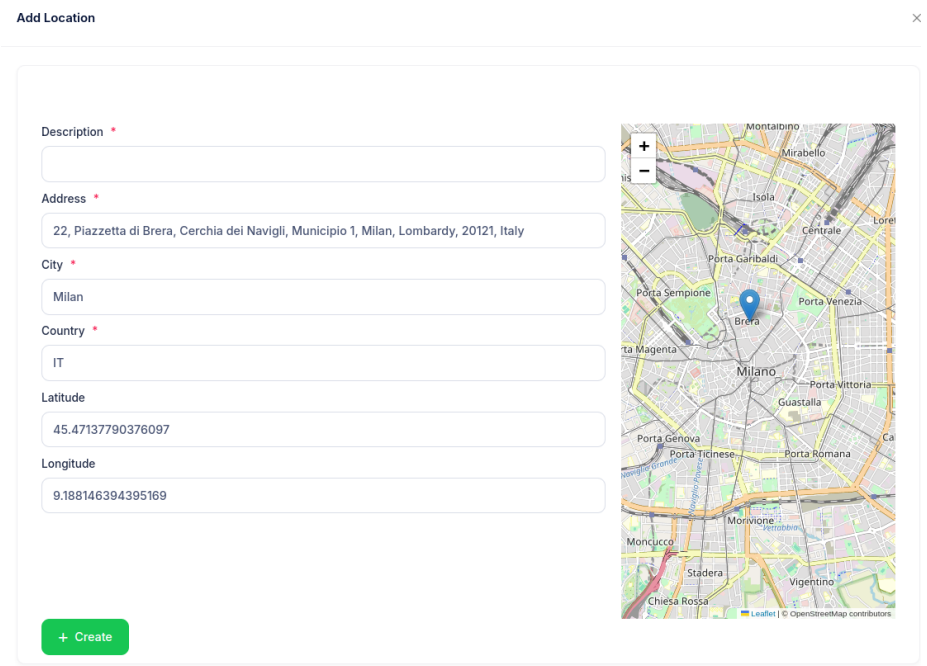

Figure 16: Add new location form (ReBuilt portal screenshot)

6.2.2 Processing and Quality Assessment

Material processing workflows manage materials through classification, testing, treatment, and preparation activities that determine appropriate reuse applications while maintaining quality standards and regulatory compliance.

Processing Event Management tracks materials through cleaning, sizing, sorting, and treatment operations while documenting processing parameters, equipment used, and quality control measures applied. Integration with processing equipment enables automatic capture of operational data while maintaining manual override capabilities for exceptional circumstances.

Figure 17 illustrates the fields associated with processing events.

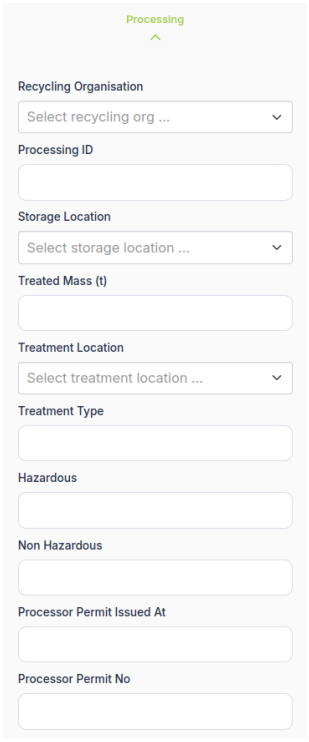

Figure 17: Form Waste Production Item Event. Processing Section (ReBuilt portal screenshot)

Displays:

- Recycling organisation
- Processing ID
- Storage Location
- Treated mass (t)
- Treatment location
- Treatment type
- Hazardous/ non-hazardous
- Processor Permit Issued data and number

Quality Assessment Documentation provides structured forms for recording material testing results, condition assessments, and technical specifications that inform reuse potential and application suitability. Standardised testing protocols ensure consistent evaluation while accommodating material-specific requirements and industry standards.

Storage and Inventory Management tracks processed materials through warehouse and outdoor storage locations while maintaining environmental monitoring data, storage conditions, and accessibility information. Real-time inventory updates support availability queries and procurement coordination while optimising storage space utilisation.

6.2.3 Digital Product Passport Generation

Digital Product Passport functionality creates comprehensive material documentation that travels with materials throughout their lifecycle while supporting regulatory compliance and buyer confidence in circular economy applications.

Automated Passport Creation generates standardised documentation using material data collected throughout processing workflows while incorporating testing results, condition assessments, and provenance information. Cryptographic signing ensures data integrity and authenticity verification for downstream users.

Multi-Format Access provides passport information through embedded web viewers, downloadable machine-readable formats, and QR code access for mobile verification. Format selection accommodates different user requirements while maintaining content consistency and verification capabilities.

Menu **Product** contains 1 sub-menu **Product, Raw Material, Product Attachment Type, Taric**. Figure 18 illustrates menu **Product.**

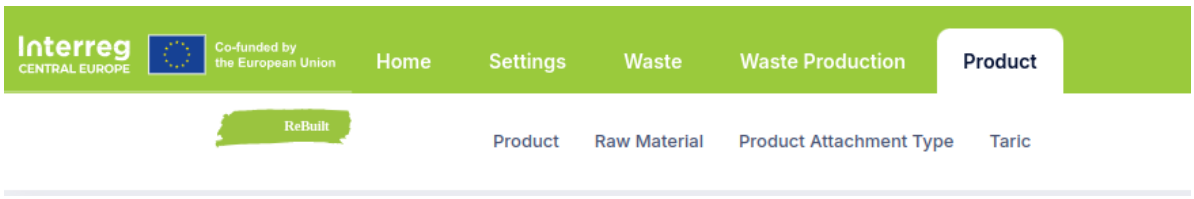

Figure 18: Product menu (ReBuilt portal screenshot)

Figure 19 shows the **Product** index section, which contains a grid listing the products.

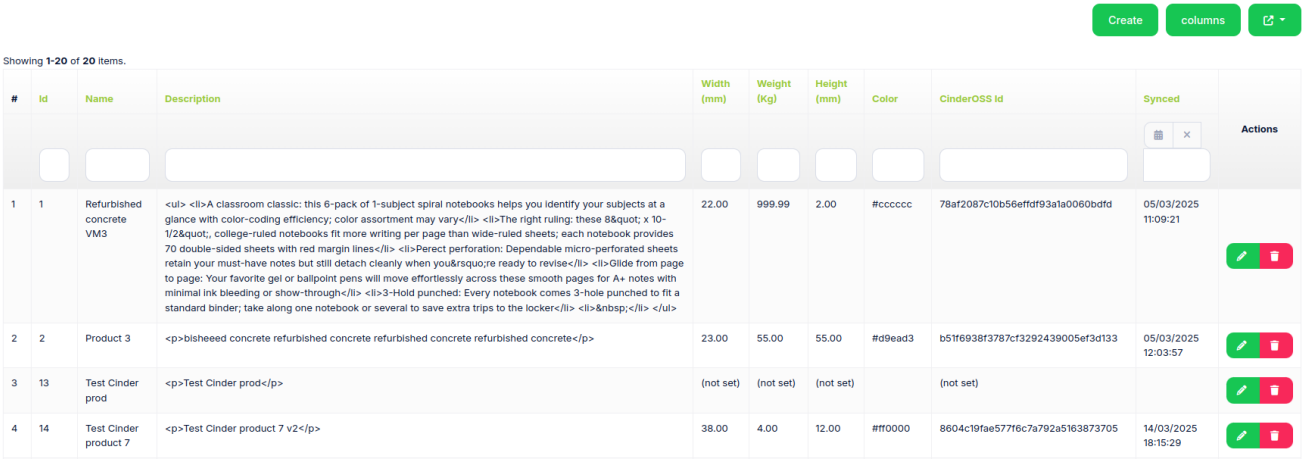

Figure 19: Product list (ReBuilt portal screenshot)

Dedicated action buttons are available in the Index section. Table 5 lists the buttons that can be used in this section.

Table 5: Action button in Product Index section

Create	Function that creates a new Product
columns	Tool to manage columns to visualise in grid view. Allow to customise grid view. Also this tool helps to manage fields according to the user permissions and field classification
HTML CSV Text PDF Excel 95 + Excel 2007+	Tool to save information from grid to file in different formats

Clicking the Columns button opens a tool to manage which columns are visible in the grid view. This allows you to show or hide specific columns and reorder them by simply dragging, as shown in Figure 20.

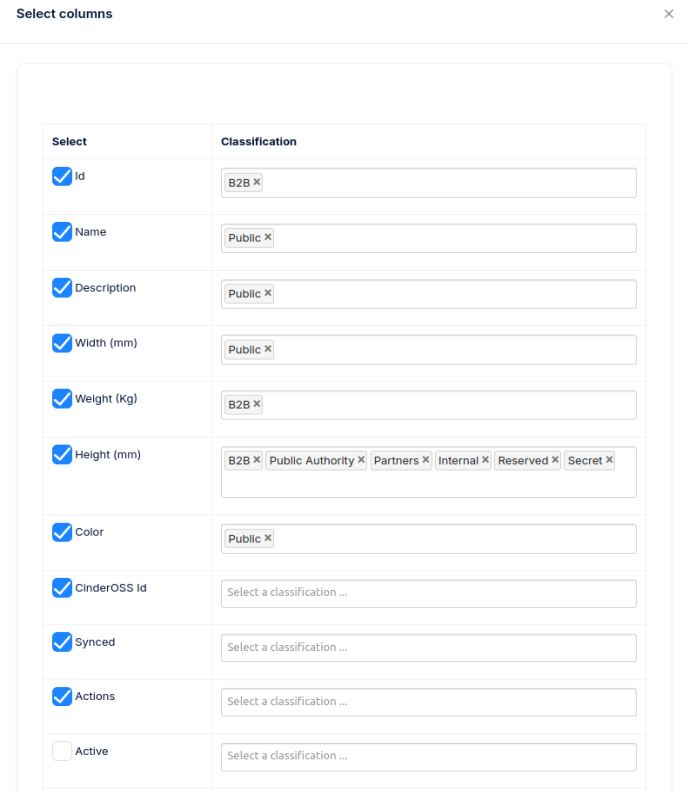

Figure 20: Tool to manage columns to visualise in grid view (ReBuilt portal screenshot)

By clicking on the pencil icon ( ), the product can be visualised and managed. Product has 4 tabs: Product, Raw Materials, DPP data, Products Attachments. Figures 21-25 show the Product details page.

6.3 User Interface Modules and Navigation

The platform organises functionality through logical module groupings that align with operational workflows while providing efficient navigation and task completion capabilities.

6.3.1 Dashboard and Overview Functions

The platform dashboard provides personalised views of relevant information and quick access to frequently used functions based on user roles and organisational responsibilities. Customizable widgets display key performance indicators, recent activities, and pending tasks while providing navigation shortcuts to detailed functionality.

Performance Metrics Display presents material processing volumes, reuse percentages, regulatory compliance status, and circular economy impact measurements through visual charts and summary statistics. Drill-down capabilities enable detailed analysis while maintaining overview perspective for executive reporting.

Activity Monitoring tracks recent system activities, pending approvals, and scheduled tasks while providing notifications for items requiring user attention. Integration with email and mobile notifications ensures timely response to critical activities while avoiding information overload.

6.3.2 Material and Product Management

Material management modules provide comprehensive functionality for tracking construction materials and products throughout their lifecycle while supporting diverse material types and processing requirements.

Material Classification and Categorisation enables systematic organisation of materials according to European Waste Catalogue codes, material types, and reuse potential while supporting custom classification schemes for organisational requirements. Hierarchical categorisation structures accommodate complex material relationships while maintaining search and reporting efficiency.

Product Catalogue Management supports creation and maintenance of product records including technical specifications, documentation attachments, and Digital Product Passport information. Multi-language support accommodates international markets while maintaining consistent technical information across different language versions.

The **Product** tab contains general information about the product: name, images, product description (which can be written using the built-in text editor), colour, dimensions, TARIC code, serial number, GTIN code. Additionally, reference information about synchronisation with CinderOSS is provided (CinderOSS ID and synchronisation time).

To enable information exchange between BIM systems, the option to download the product description in IFC format has been implemented (By clicking the **Download IFC file** button, the file is downloaded).

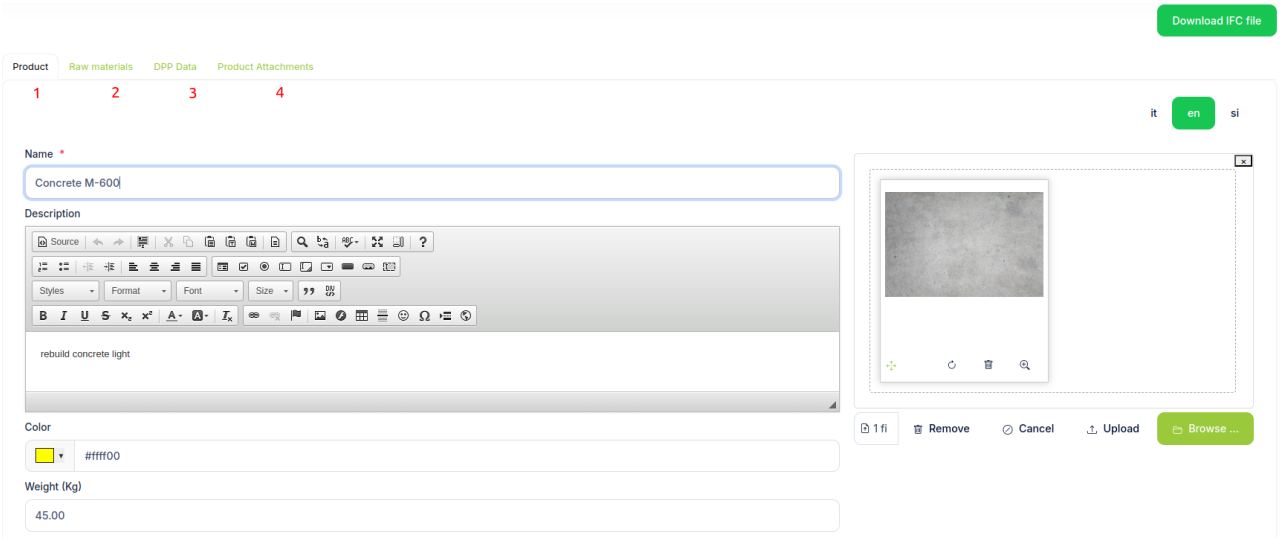

Figure 21: Product details (ReBuilt portal screenshot)

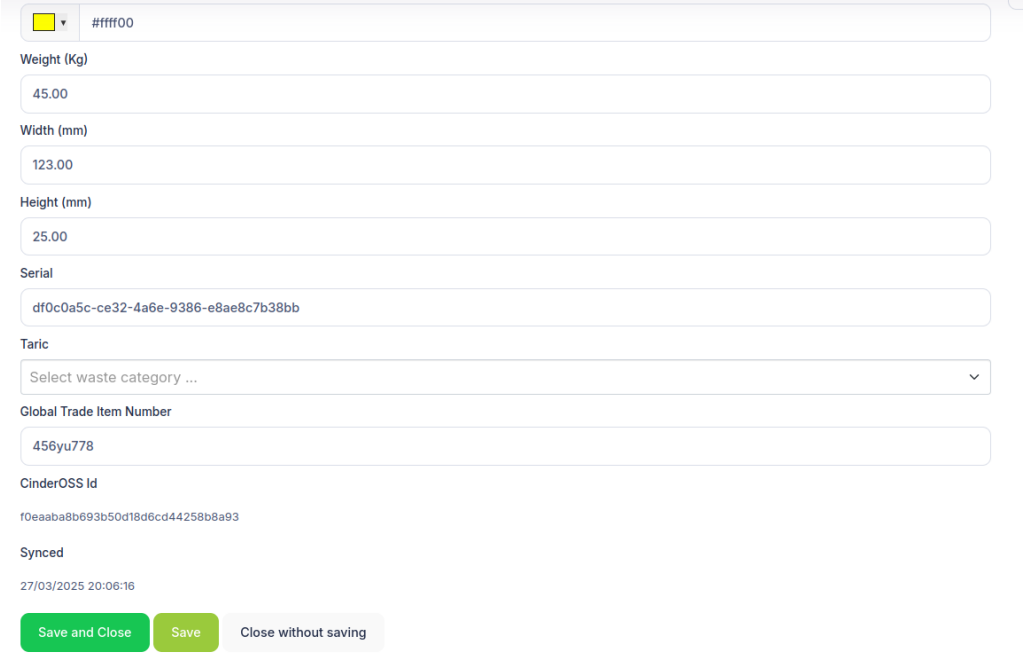

Figure 22: Product details (continue) (ReBuilt portal screenshot)

Raw Material Tracking connects processed raw materials with source waste materials while documenting transformation processes and yield calculations. This functionality supports complete material provenance tracking while enabling optimisation of processing efficiency and resource utilisation.

In the **Raw Materials** tab, the unit and quantity of raw materials included in the product are displayed.

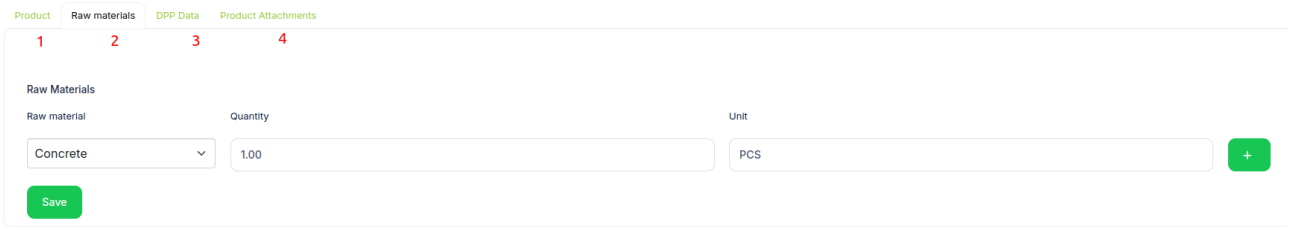

Figure 23: Raw Materials tab in Product (ReBuilt portal screenshot)

By clicking on the icon +, you can add new row materials to the product or delete them ( ).

In the **DPP Data** tab, the Digital Product Passport is presented. The attributes of the passport are set in the general settings under the **Custom fields** menu and can be accessed at:

https://rebuilt.way.to.it/custom-field/

If you need to modify the composition of the passport attributes, please refer to the documentation in the Custom fields section.

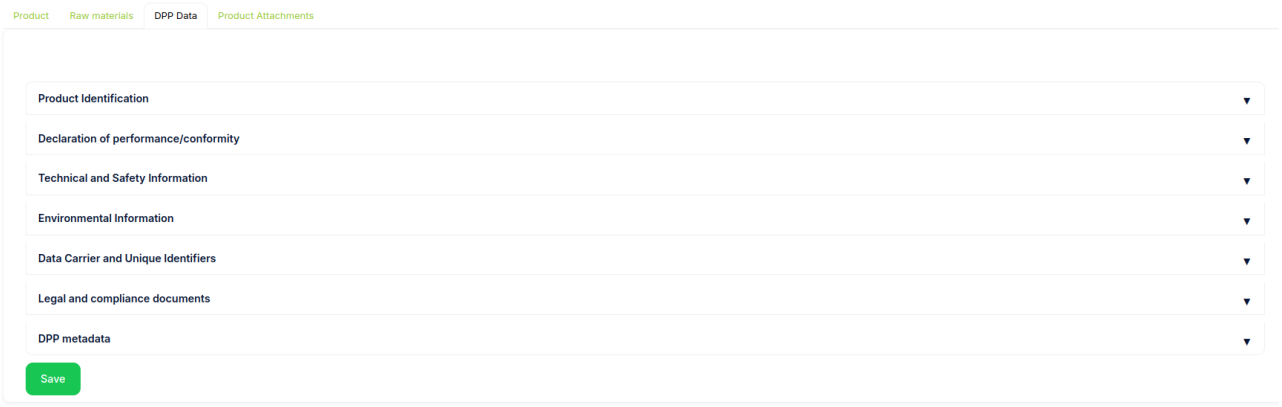

Figure 24: DPP Data tab in Product (ReBuilt portal screenshot)

The **Product Attachments** tab displays a list of files attached to the product. Each attachment is assigned a **Description**, an **Attachment Type** (selected from the catalogue **Attachment Type** https://rebuilt.way.to.it/product-attachment-type, e.g., **CE Certificate, Operator Manual**, etc.), **IPR**, and a **Classification** (selected from the catalogue **Classification** https://rebuilt.way.to.it/classification, which defines accessibility for different access types). In this tab, you can manage attachments by **adding or editing** them.

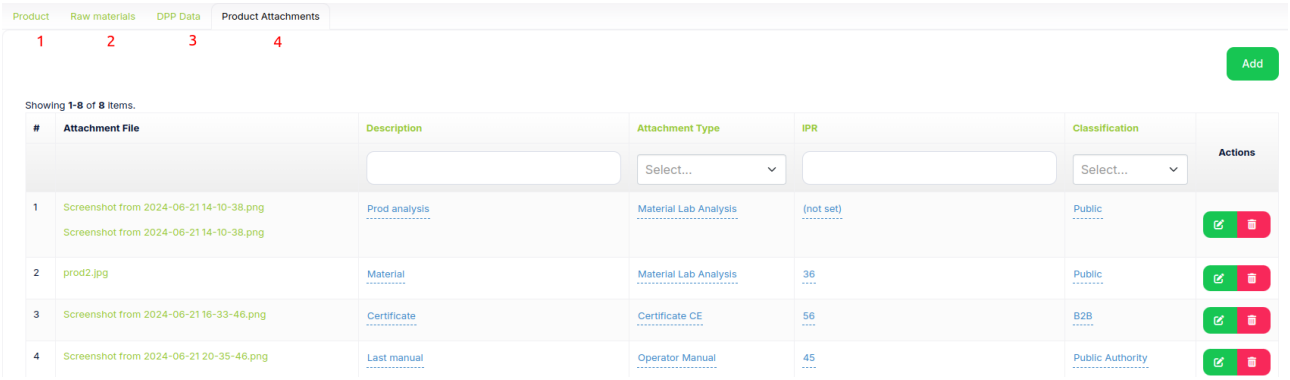

Figure 25: Product Attachments tab in Product (ReBuilt portal screenshot)

By clicking on the Add button, you can add a new attachment. Figure 26 shows the form for adding Product Attachments. When adding an attachment, the **access type** must be specified in the **Classification** field.

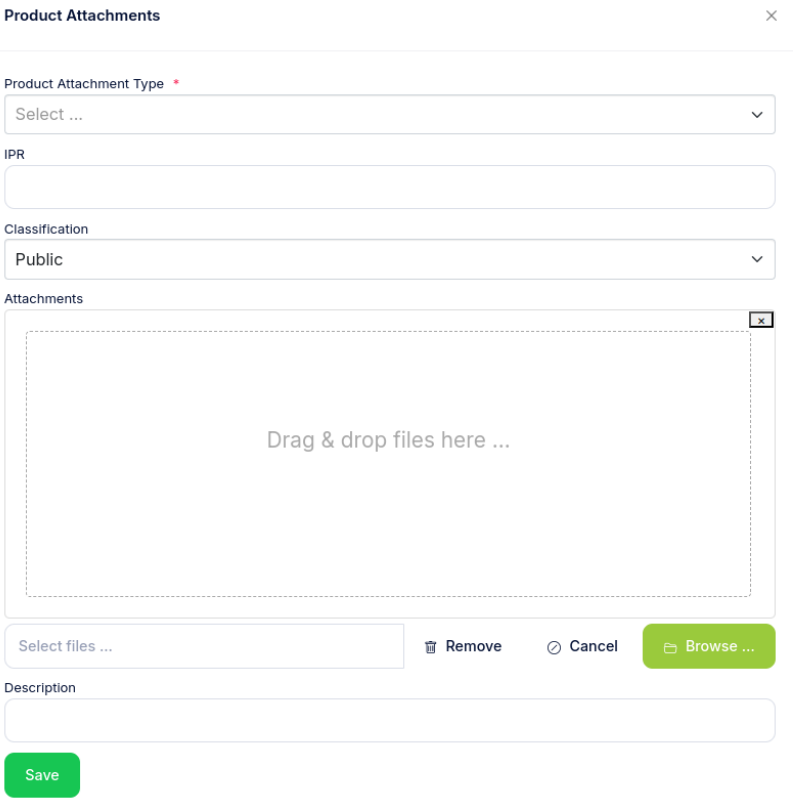

Figure 26: Add Attachment (ReBuilt portal screenshot)

Additionally, attributes can be edited directly in the list by clicking the desired field and making the necessary changes, as shown in Figure 27.

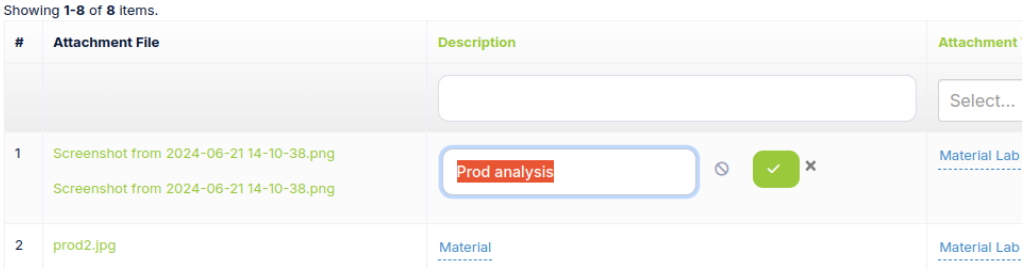

Figure 27: Editing attributes directly in list of attachments (ReBuilt portal screenshot)

Figure 28 shows the **Raw Material** index section, which contains a grid listing the raw materials.

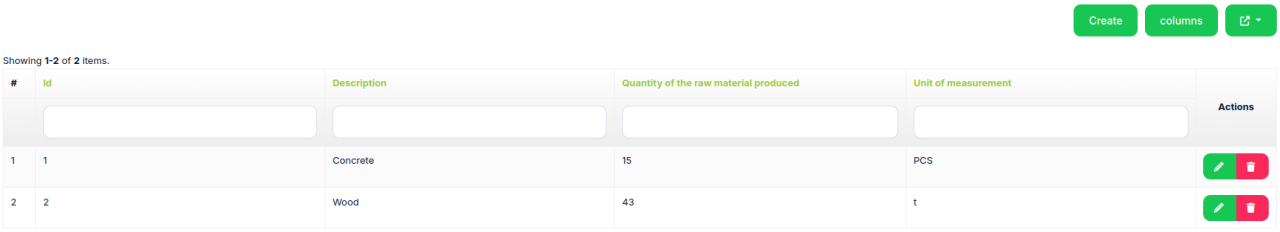

Figure 28: Raw Material list (ReBuilt portal screenshot)

Dedicated action buttons are available in the Index section. Table 6 lists the buttons that can be used in this section.

Table 6: Action button in Raw Materials Index section

Create	Function that creates a new Raw Material
columns	Tool to manage columns to visualise in view grid. Allow to customise grid view
HTML CSV Text PDF Excel 95 + Excel 2007+	Tool to save information from grid to file in different formats

By clicking on the pencil icon ( ), the raw material can be visualised and managed. Figure 29, 30 shows the Raw Material detail page. Raw material has 2 tabs: Raw material and Waste Production Items.

In the Raw Material tab, the description, quantity of raw materials produced, and unit of measurement are displayed.

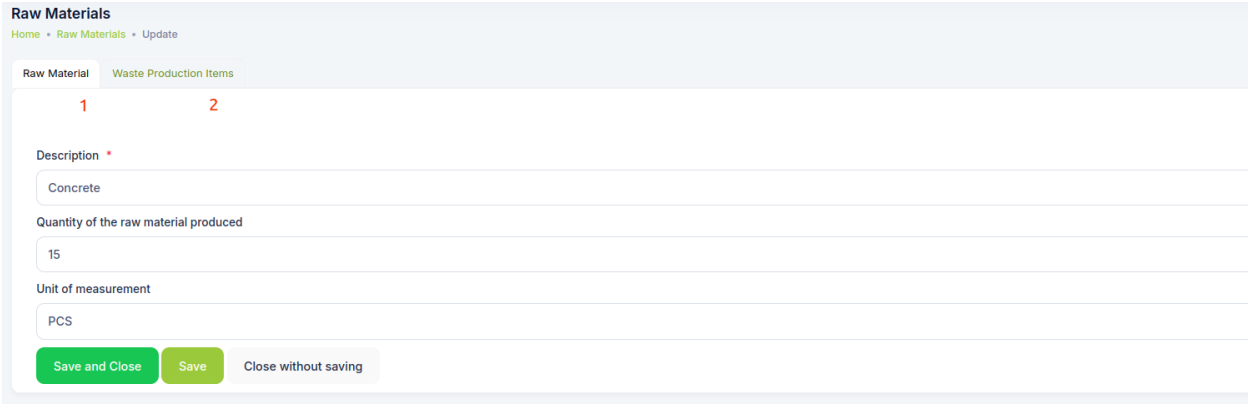

Figure 29: Raw Material tab (ReBuilt portal screenshot)

The **Waste Production Items** tab displays the initial waste materials that are collected and processed into raw materials. These items include various types of industrial and construction waste, such as glass, concrete, plastic etc. Each item listed here serves as a source material for further recycling and production. For example, concrete waste is crushed and used to create construction aggregates, while glass is melted down to produce new glass products. This tab shows the types of waste received, their quantities, and units of measurement, helping to track the input materials used in the recycling process.

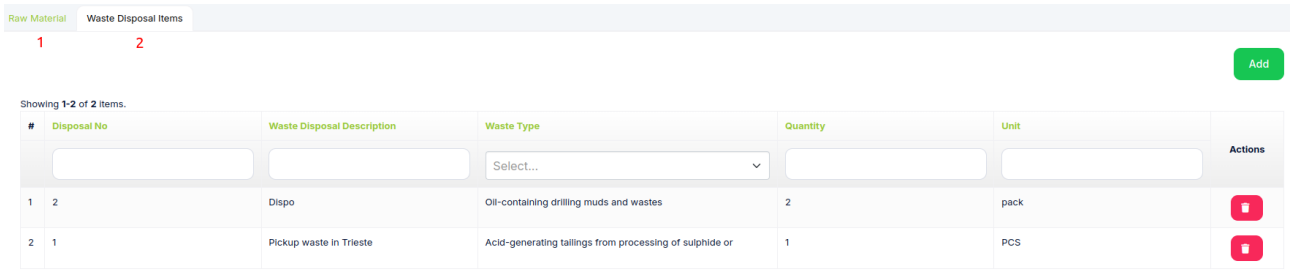

Figure 30: Waste Production Items tab (ReBuilt portal screenshot)

As shown in Figure 31, clicking the **Add** button opens a modal window for adding Waste Production Items from the Waste Production Items catalogue.

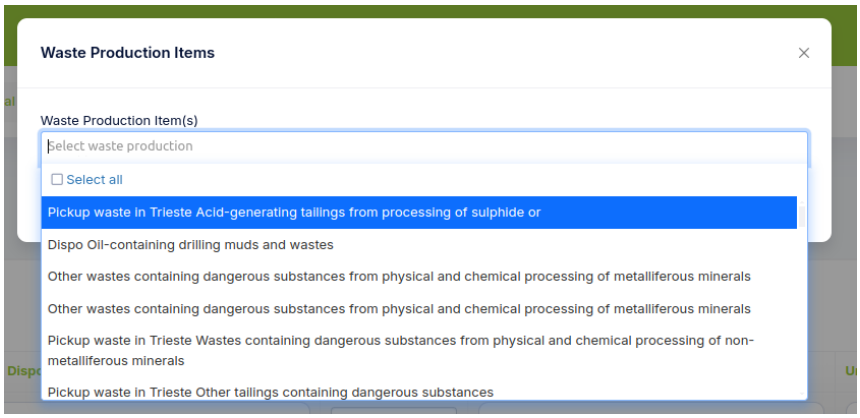

Figure 31: Modal window for adding Waste Production Items from catalogue (ReBuilt portal screenshot)

Figure 32 shows the **Product Attachment Type** index section, which contains a list of types that can be set to attachment.

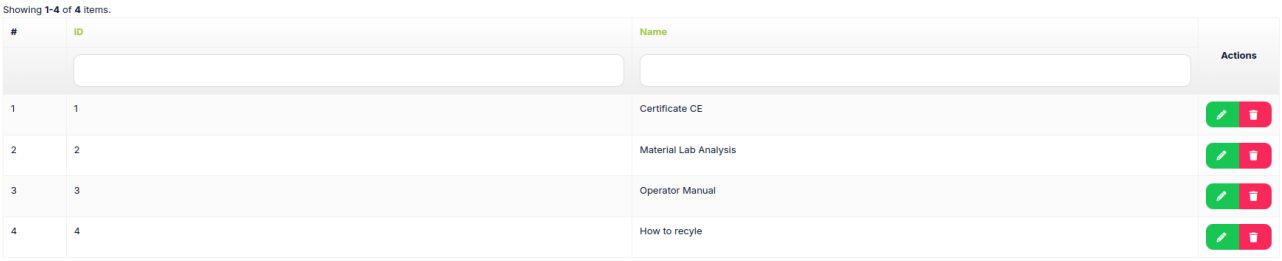

Figure 32: Product attachment type list (ReBuilt portal screenshot)

Figure 33 shows the **Taric** index section contains a list of TARIC codes. Contains information about the TARIC code: Measure Type, Duty Rate, Country of Origin and Code Validity Period.

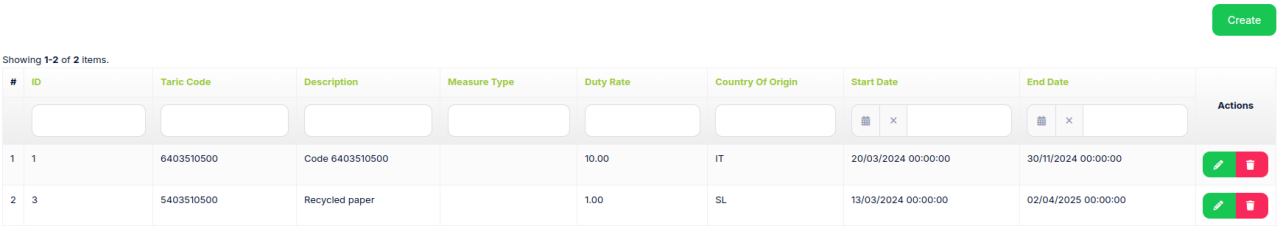

Figure 33: List of TARIC Codes (ReBuilt portal screenshot)

By clicking on the pencil icon ( ), the TARIC record can be visualised and managed, as shown in Figure 34.

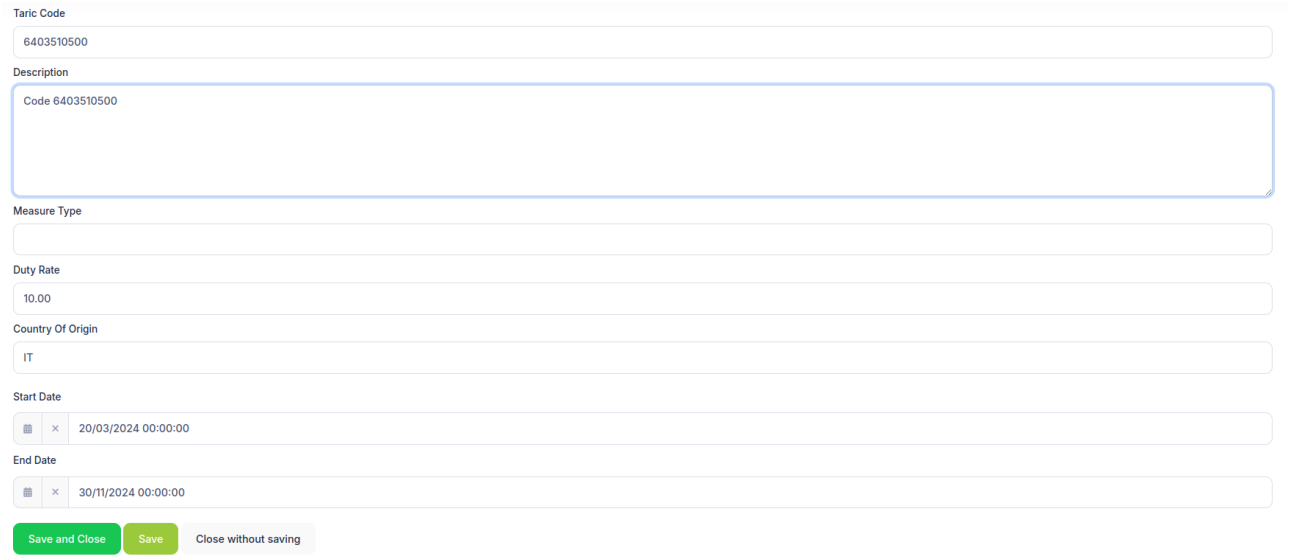

Figure 34: Details for TARIC Code (ReBuilt portal screenshot)

6.3.3 Organisational and Location Management

Administrative modules provide comprehensive organisational and location management capabilities that support multi-tenant operations while maintaining appropriate data segregation and access controls.

Organisation Profile Management enables creation and maintenance of detailed organisational records including contact information, certifications, operational capabilities, and service areas. Integration with user management systems ensures appropriate access controls while supporting collaborative workflows across organisational boundaries.

Location and Facility Management provides geographic information management for all material handling locations, including processing facilities, storage areas, and transportation hubs. GPS coordination integration supports precise location tracking while mapping interfaces provide visual location management and routing optimisation.

User Access and Permission Management implements comprehensive role-based access control that aligns system permissions with organisational structures and operational responsibilities. Granular permission settings enable precise control over data access and functional capabilities while maintaining audit trails for security and compliance requirements.

Within the system configuration, **general system parameters** related to locations, custom fields that describe DPP data, user and organisation management can be administered. Figure 35 illustrates the Settings menu.

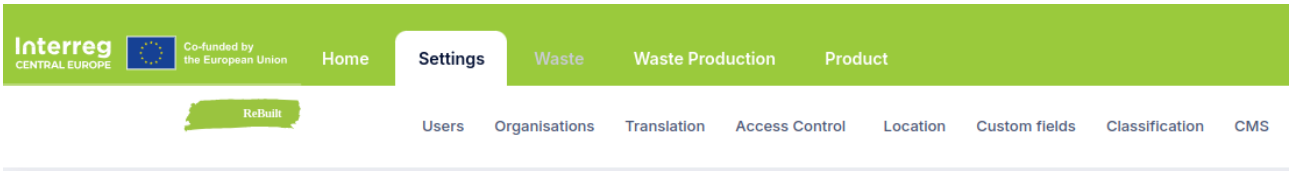

Figure 35: Settings menu (ReBuilt portal screenshot)

Figure 36 shows the list of users who have access to the portal. Access to the system is done with a personal account. Each user must be linked to an organisation. For each user, granular access control roles can be defined to access and manage system resources.

The Portal offers the RBAC Methodology (Role-Based Access Control), enabling the definition of specific roles and policies for user groups.

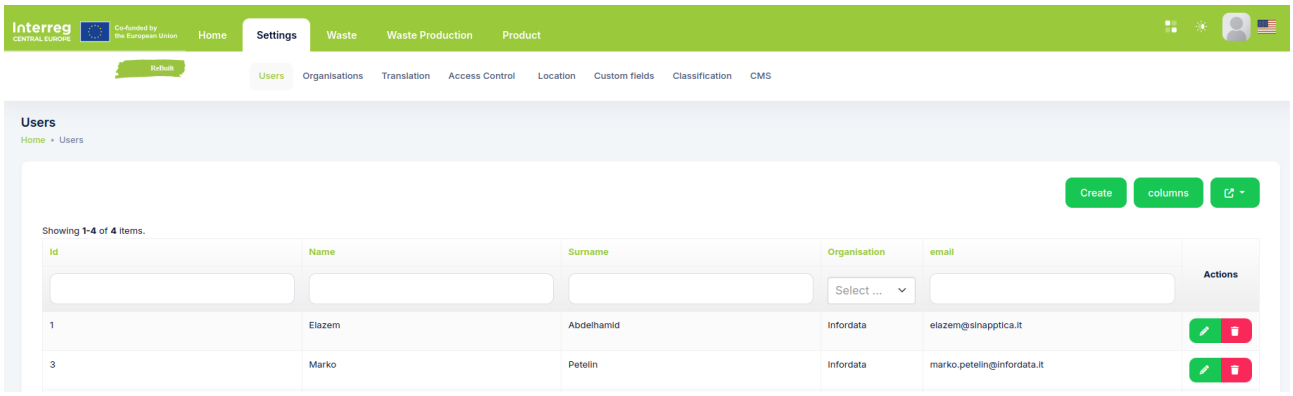

Figure 36: Users list (ReBuilt portal screenshot)

As shown in Figure 37, clicking the pencil icon in the grid view allows you to access user details, update data, assign an RBAC profile, and set a new password.

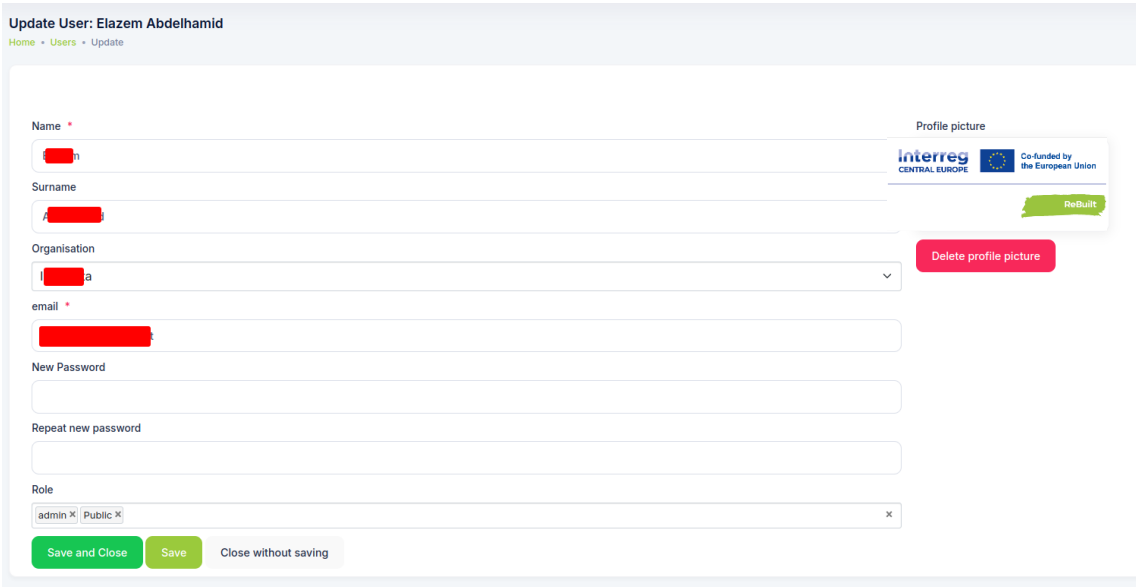

Figure 37: User details (ReBuilt portal screenshot)

Figure 38 shows the list of organisations that are enabled in the system.

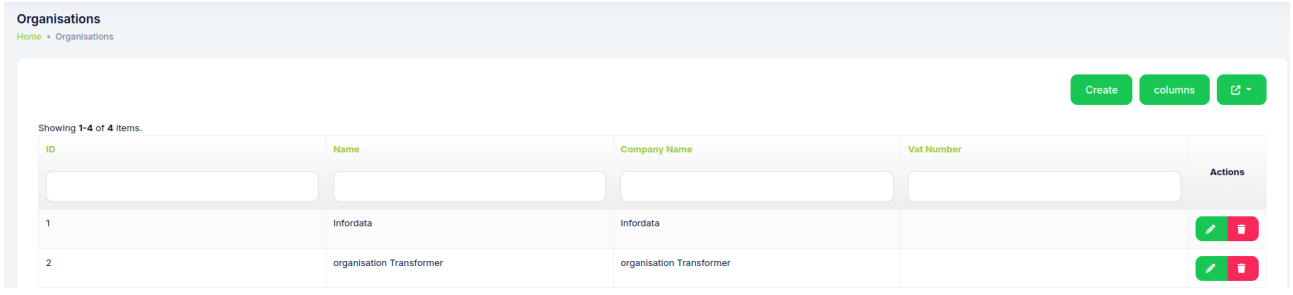

Figure 38: Organisations list (ReBuilt portal screenshot)

This section allows the management of organisations that are enabled in the system.

Click on the **Create** button to add a new organisation and fill in the required fields. If the organisation already exists, select it from the grid list by clicking on the pencil icon. When editing an organisation, there are three tabs: Organisation, Waste Production Log, Locations, as shown in Figure 39, 40, 42.

The **Organisation** tab includes general details such as the company name, VAT number, Tax code, contact email, address, type (Supplier, Demolishing, Recycling, Transporter) company logo, etc.

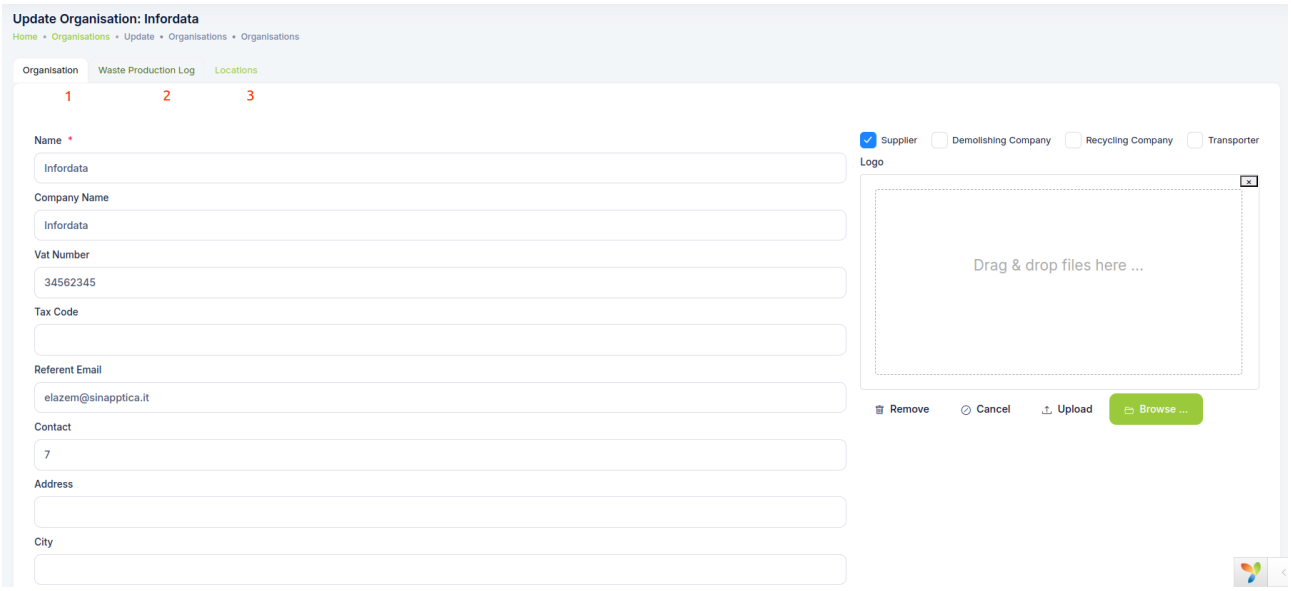

Figure 39: Details of Organisation (ReBuilt portal screenshot)

The **Waste Production Log** Tab includes a list of all waste production for the edited organization. Here, you can also create a new one or edit an existing waste production.

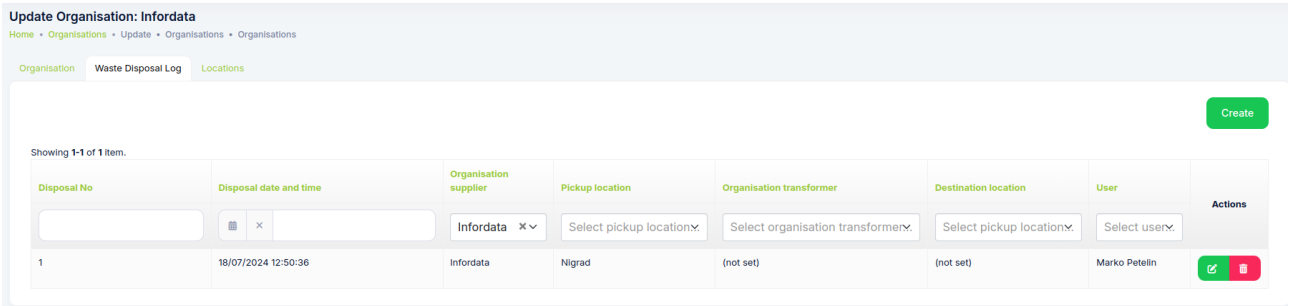

Figure 40: List of waste production for edited organisation (ReBuilt portal screenshot)

By clicking the **Create** or **Edit** button, a modal window opens where you can fill in details of the waste production, as shown in Figure 41.

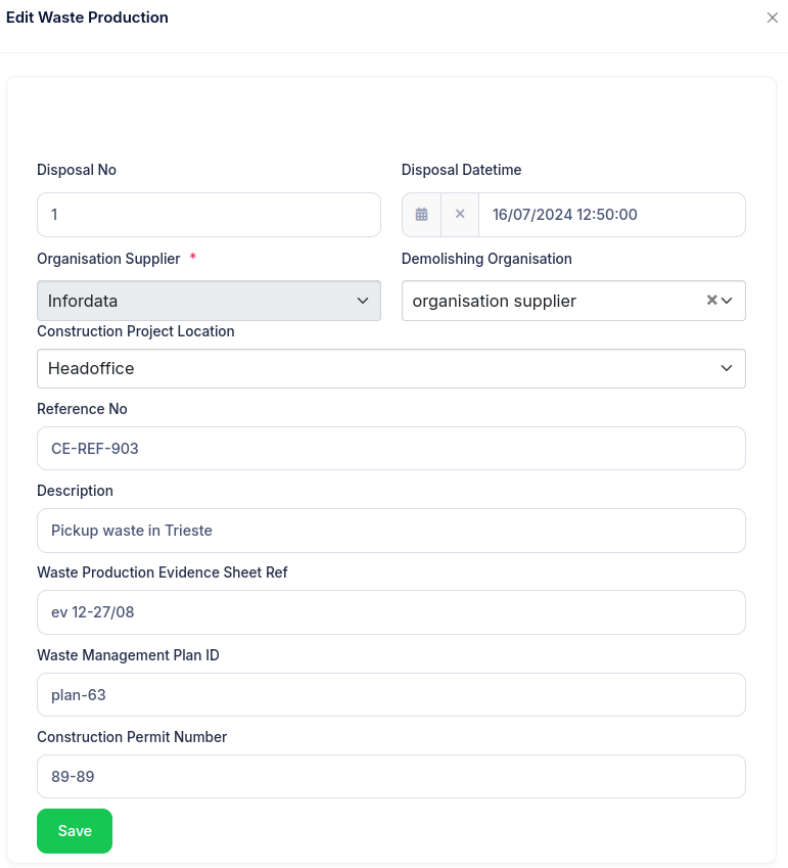

Figure 41: Modal window for edit details of waste production (ReBuilt portal screenshot)

The **Locations** Tab includes a list of all locations for the edited organisation. Here, you can also add a new location or edit an existing one.

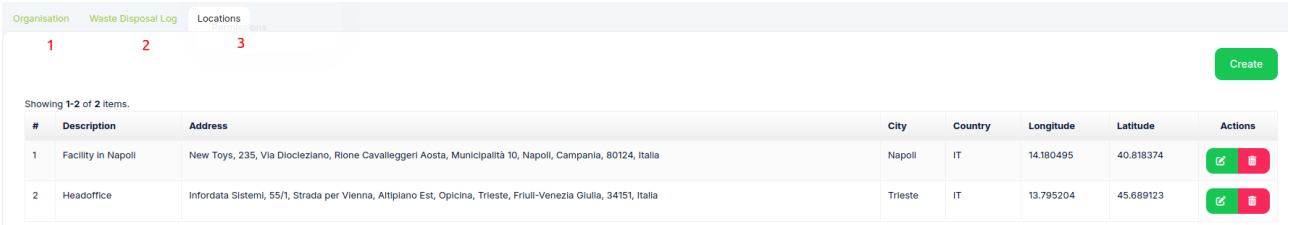

Figure 42: List of locations for edited organisation (ReBuilt portal screenshot)

Figure 43 illustrates the list of all locations utilised in the portal.

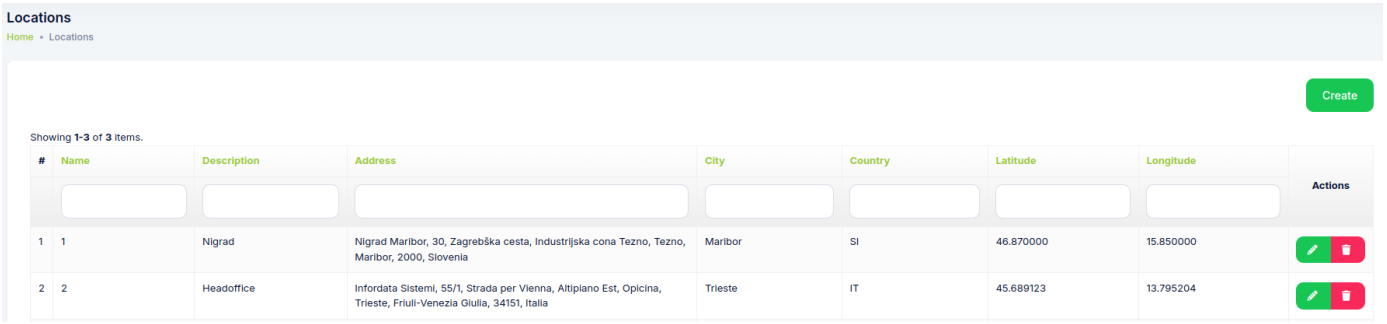

Figure 43: Locations list (ReBuilt portal screenshot)

In the Location section, specific functions are employed to create or manage locations, set GPS coordinates manually or choose from a map. Figure 44 shows the form for create/edit location.

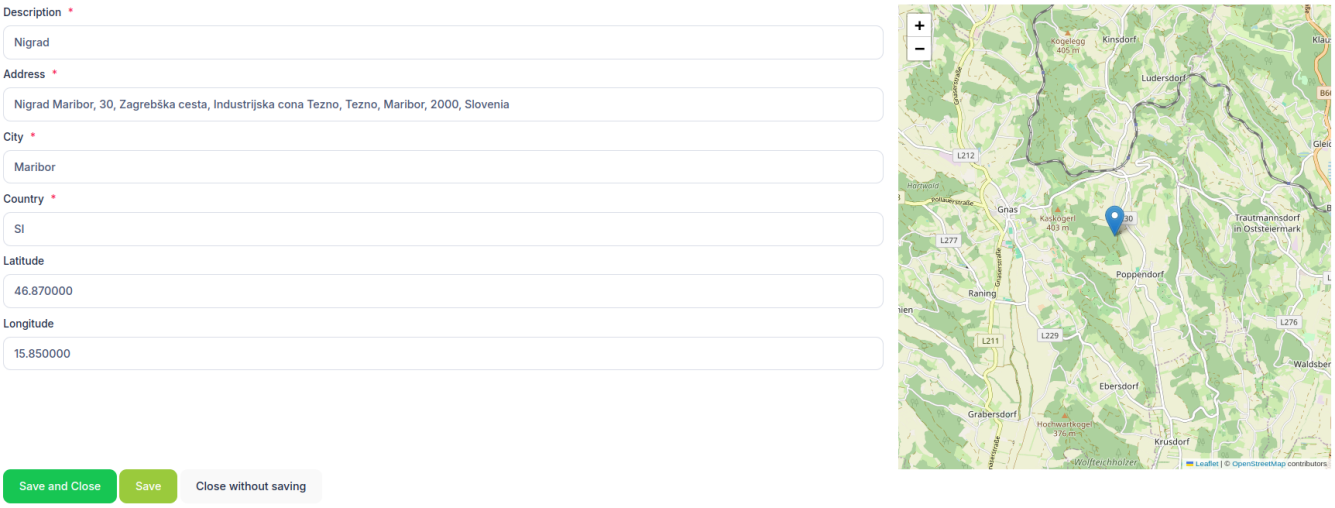

Figure 44: Detail of location (ReBuilt portal screenshot)

In the **Custom Field** section, specific functions are employed to create or manage DPP data. You can add and reorder attributes necessary for DPP data using the built-in editor, as shown in Figure 45.

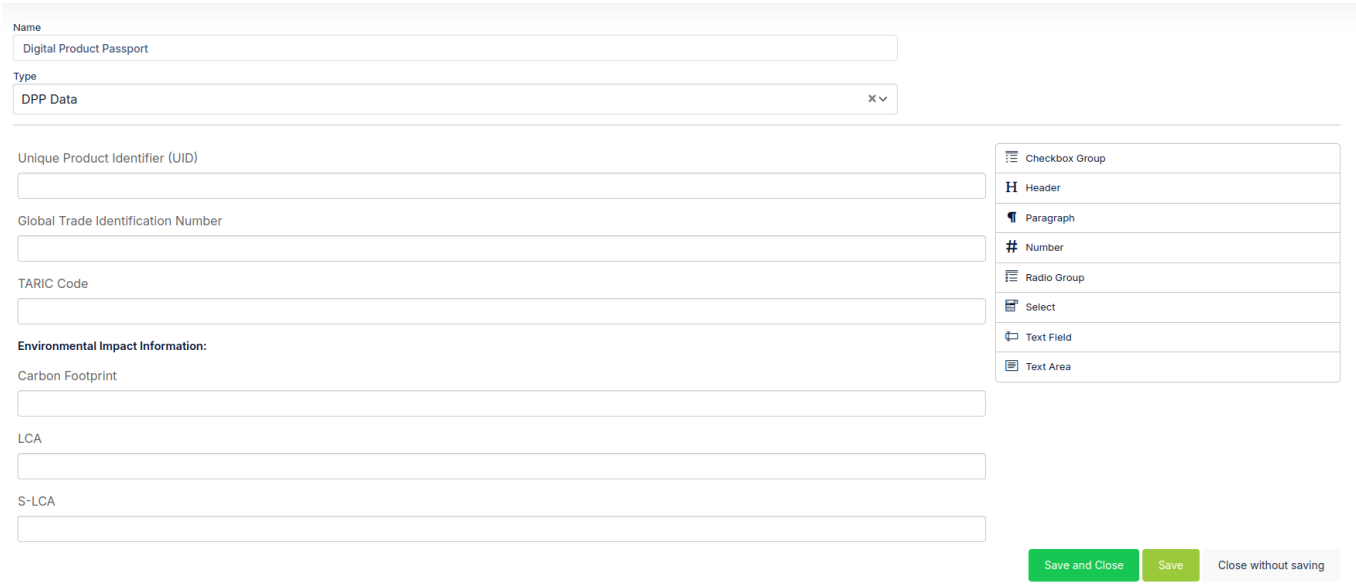

Figure 45: Custom fields edit form (ReBuilt portal screenshot)

Classifications

In the **Classification** section, there are specific functions for creating and managing classifications for product attachment types, as well as assigning roles to specific classifications. Figure 46 shows a list of Classification.

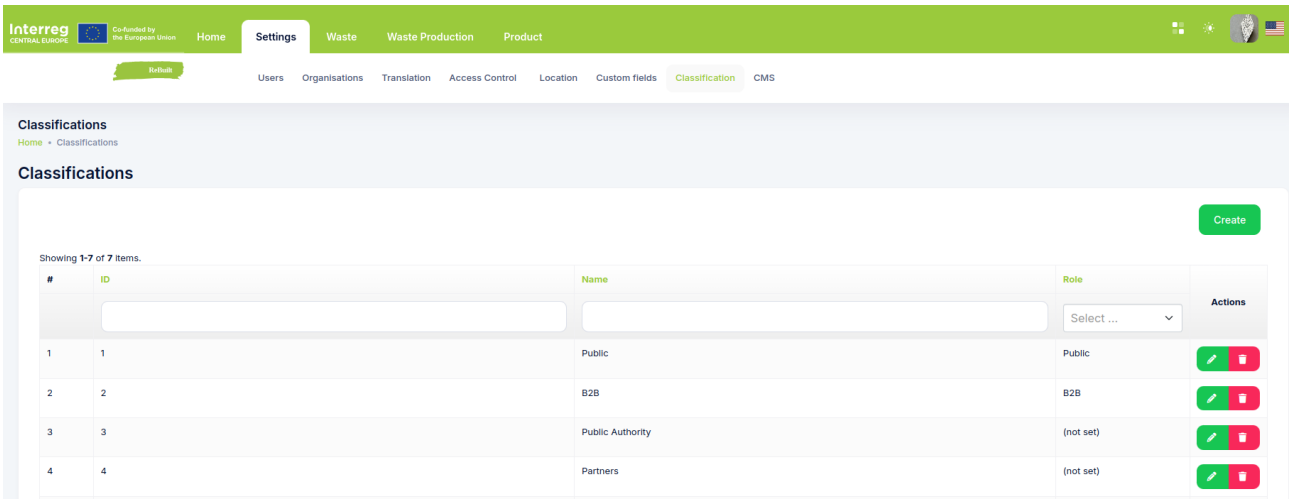

Figure 46: List of Classifications (ReBuilt portal screenshot)

Clicking the **Create** button allows you to add a new Classification, or clicking the Edit button opens the form for adding/editing a classification and assigning it to a role. The form is shown in Figure 47.

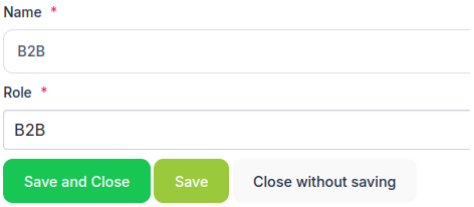

Figure 47: Assign role for specific classification (ReBuilt portal screenshot)

The **CMS** section lists the CMS pages displayed in the portal frontend (e.g., About, Homepage, Contact), as shown in Figure 48.

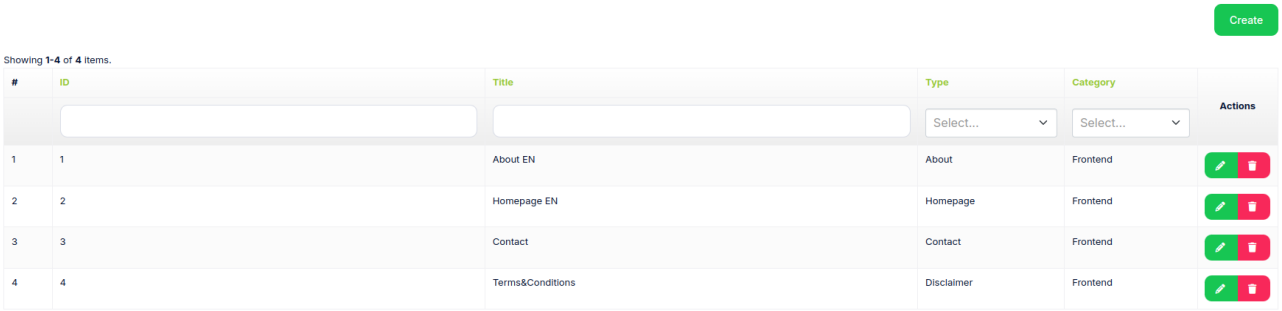

Figure 48: List of CMS pages (ReBuilt portal screenshot)

Users can edit or add new CMS pages using the built-in HTML editor. Figures 49, 50 illustrate the details of an edited CMS page.

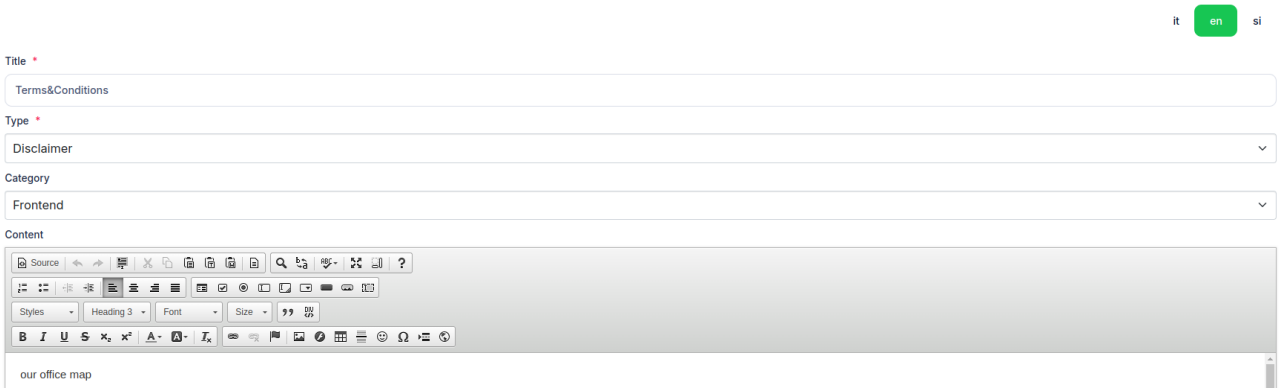

Figure 49: Detail for CMS page (ReBuilt portal screenshot)

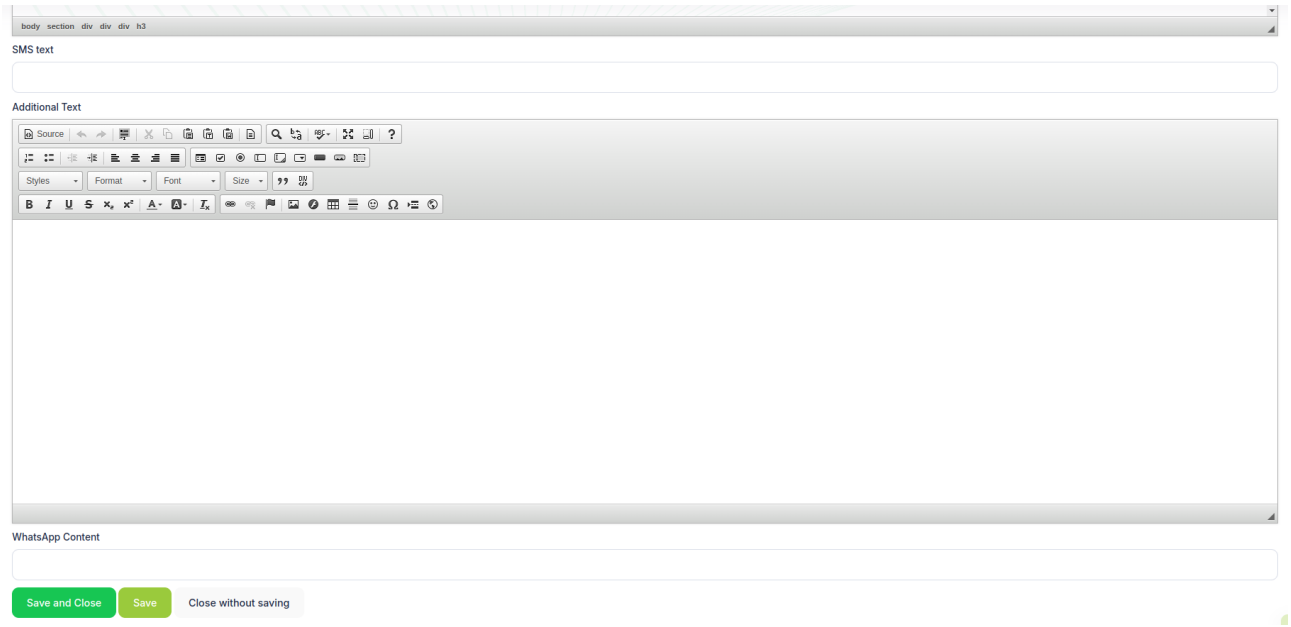

Figure 50: Details for CMS page (continue) (ReBuilt portal screenshot)

6.4 Reporting and Analytics Capabilities

The platform provides comprehensive reporting and analytics functionality that supports operational management, regulatory compliance, and strategic decision-making across diverse organisational requirements.

6.4.1 Operational Reporting

Standard operational reports provide insights into material processing efficiency, inventory status, and workflow performance while supporting continuous improvement initiatives and capacity planning activities.

Material Flow Analysis tracks materials through complete lifecycle stages while identifying bottlenecks, optimisation opportunities, and process improvements. Visual workflow diagrams illustrate material pathways while quantitative analysis supports efficiency measurement and performance optimisation.

Inventory and Availability Reports provide real-time information about available materials including quantities, locations, conditions, and reuse potential assessments. Integration with procurement systems enables automated availability checking while supporting demand forecasting and capacity planning.

6.4.2 Regulatory and Compliance Reporting

Automated regulatory reporting capabilities generate required documentation for waste management authorities, environmental agencies, and circular economy performance measurement while maintaining comprehensive audit trails and verification procedures.

Waste Management Compliance generates required waste tracking documentation, transportation manifests, and disposal certificates while maintaining regulatory compliance across multiple jurisdictional requirements. Automated data validation ensures accuracy while reducing administrative overhead and compliance risks.

Circular Economy Performance Metrics calculate material reuse percentages, waste diversion rates, and environmental impact reductions while supporting sustainability reporting and

certification requirements. Integration with industry standards ensures consistent measurement methodologies while accommodating organisational reporting preferences.

6.4.3 Business Intelligence and Decision Support

Advanced analytics capabilities provide strategic insights for business optimisation, market development, and sustainability improvement while supporting data-driven decision-making across operational and strategic levels.

Predictive Analytics utilises historical data patterns to forecast material availability, processing capacity requirements, and market demand while supporting proactive planning and resource optimisation. Machine learning algorithms identify trends and optimisation opportunities while maintaining interpretable results for management decision-making.

Market Intelligence analyses material reuse patterns, pricing trends, and demand characteristics while supporting strategic planning for circular economy market development. Integration with external market data provides comprehensive market insights while maintaining competitive intelligence capabilities.

6.5 Integration and Interoperability Features

Platform integration capabilities enable seamless connectivity with external systems while maintaining data consistency and security across diverse technical environments and organisational requirements.

Comprehensive API functionality provides programmatic access to all platform capabilities while maintaining appropriate security controls and performance optimisation for automated system integration.

RESTful API Implementation follows industry standards for data formats, authentication methods, and error handling while providing comprehensive documentation and testing tools for third-party integration development. Rate limiting and monitoring ensure system availability while preventing abuse and unauthorised access.

Data Exchange Formats support multiple industry standards including JSON, XML, and IFC formats while providing transformation capabilities for legacy system integration. Schema validation ensures data quality while flexible mapping accommodates diverse external system requirements.

6.5.1 BIM and CAD Integration

Building Information Modelling (BIM) integration enables incorporation of material tracking data into architectural and engineering workflows while supporting sustainable design practices and construction project coordination.

IFC Export Functionality generates industry-standard building information models that include material specifications, tracking identifiers, and Digital Product Passport references. Integration with major BIM software platforms enables seamless incorporation into design and construction workflows while maintaining material traceability throughout project lifecycles.

Design Decision Support provides real-time material availability information within design environments while enabling sustainability impact assessment and circular economy optimisation during design development phases. Automated calculations support green building certification requirements while optimising material selection decisions.

6.6 Mobile Application Capabilities

Mobile applications provide field-optimised access to essential platform functionality while supporting offline operation and automatic synchronisation capabilities appropriate for construction site environments.

6.6.1 Field Data Collection

Mobile interfaces prioritise rapid data entry and material identification capabilities while maintaining data quality through validation and user guidance systems optimised for field conditions.

Material Scanning and Identification utilises smartphone cameras for QR code and barcode scanning while providing manual data entry capabilities for materials without existing identifiers. Offline capability ensures continued operation during network connectivity interruptions while automatic synchronisation maintains data consistency.

Visual Documentation enables photographic documentation of material conditions, processing activities, and storage locations while maintaining GPS location data and timestamp information. Image compression and optimisation reduce storage requirements while maintaining sufficient quality for assessment and verification purposes.

6.6.2 Workflow Coordination

Mobile applications support coordination between field operations and central management systems while providing real-time status updates and communication capabilities.

Task Management and Notifications provide mobile access to assigned tasks, pending approvals, and priority activities while enabling status updates and completion confirmation from field locations. Push notification integration ensures timely communication while avoiding information overload during active work periods.

Real-Time Communication enables coordination between field personnel, processing facility operators, and management systems while maintaining context-aware information sharing and escalation procedures. Integration with existing communication systems supports workflow continuity while providing platform-specific coordination capabilities.

7 Database Schema Description

The platform's database architecture implements a normalised relational schema designed to support comprehensive material lifecycle tracking while maintaining data integrity, query performance, and scalability across diverse operational requirements. Built on MySQL with InnoDB storage engine, the schema balances normalised design principles with practical performance optimisation for material tracking workflows.

7.1 Schema Design Principles and Architecture

The database design follows established relational modelling principles while incorporating specific optimisations for material traceability requirements, temporal data management, and multi-tenant operations.

Normalisation and Data Integrity ensure that material information, organisational data, and operational records maintain consistency while eliminating redundancy and supporting efficient updates. Foreign key constraints enforce referential integrity across related entities while cascade operations maintain data consistency during record lifecycle management.

Temporal Data Management accommodates the time-dependent nature of material status, location changes, and processing events through timestamp fields and audit trail maintenance. Historical data preservation supports regulatory compliance and lifecycle analysis while maintaining query performance for current operational data.

Scalability Considerations include strategic indexing for common query patterns, partitioning strategies for large tables, and denormalisation where appropriate for reporting performance. Connection pooling and query optimisation support concurrent user operations while maintaining transaction consistency.

Security and Access Control integrate with application-layer security through role-based data access patterns, sensitive data encryption, and comprehensive audit logging that supports compliance requirements while maintaining operational efficiency.

7.2 Core Entity Groups and Relationships

The schema organises entities into logical groups that reflect material lifecycle workflows while maintaining clear relationships and data dependencies.

7.2.1 Material and Product Entities

The material management entity group forms the core of the tracking system, providing comprehensive documentation for materials throughout their lifecycle.

Product and Raw Material Relationship connects processed products with their constituent raw materials through a many-to-many relationship that maintains quantity information and processing history. This design supports complete material provenance tracking while enabling complex product compositions and recipe management.

Material Classification System utilises hierarchical categorisation through waste types and categories that align with European regulatory frameworks while supporting organisational classification extensions. The relationship between products, raw materials, and waste types enables comprehensive regulatory reporting and reuse potential assessment.

Digital Product Passport Integration links passport documentation directly to product records while maintaining versioning and signature information in separate entities. This design supports passport evolution while preserving historical documentation and enabling cryptographic verification of current and past versions.

7.2.2 Organisational and Location Management

Organisational entities support multi-tenant operations while maintaining appropriate data segregation and collaboration capabilities.

Organisation Hierarchy and Relationships accommodate complex organisational structures through parent-child relationships while supporting multiple organisation types including suppliers, processors, transporters, and recycling companies. Boolean flags enable efficient filtering while maintaining flexibility for organisations serving multiple roles.

Location and Geographic Information provides comprehensive geographic data management through separate location entities that can be shared across organisations while maintaining precise coordinate information and address normalisation. The many-to-many relationship between organisations and locations supports complex operational structures while maintaining geographic accuracy.

User Management and Access Control integrates organisational membership with role-based access control through authentication entities that support both internal user management and external system integration. The relationship between users and organisations enables appropriate data segregation while supporting collaborative workflows.

7.2.3 Operational Workflow Entities

Workflow entities capture the operational processes that transform materials through their lifecycle while maintaining comprehensive audit trails and status tracking.

Waste Production and Processing Workflow connects waste disposal records with individual waste items and their subsequent processing events through a hierarchical structure that maintains traceability while supporting batch processing operations. This design enables detailed tracking of individual materials while supporting efficient bulk operations.

Event Tracking and Status Management utilises a flexible event model that accommodates diverse processing activities including transportation, treatment, storage, and quality assessment. Status fields with timestamps provide current state information while event records maintain complete historical activity logs.

Quality Assessment and Documentation integrates testing results and condition assessments directly with material records while supporting attachment management for supporting documentation. This design ensures quality information travels with materials while maintaining organised documentation access.

7.3 Detailed Entity Descriptions and Relationships

This section provides comprehensive documentation of key database entities, their relationships, and design rationale.

7.3.1 Core Material Tracking Tables

Product Table Structure serves as the central entity for processed materials and finished products, containing essential identification and specification information.

The product table includes technical specifications (dimensions, weight, colour), regulatory information (TARIC codes, GTIN), and lifecycle tracking fields (creation timestamps, synchronisation status). Custom fields stored as JSON enable flexible attribute management while maintaining query performance for standard attributes.

Foreign key relationships connect products to TARIC classification, while many-to-many relationships through pivot tables link products to raw materials with quantity information. Attachment relationships enable comprehensive documentation management while maintaining organised file storage.

Raw Material Management provides the foundation for tracking materials produced from waste processing activities while maintaining connections to source waste streams.

Raw material records include processing yield information, quality specifications, and availability status while maintaining relationships to source waste disposal items through pivot tables. This design enables complete material provenance tracking while supporting inventory management and reuse coordination.

Waste Disposal and Item Tracking captures the initial stages of material lifecycle management when materials enter the circular economy system.

Waste disposal records provide batch-level information including source location, responsible organisations, and regulatory documentation references. Individual waste disposal items maintain specific material information including type classification, quantities, and unique batch identifiers that enable granular tracking throughout subsequent processing stages.

7.3.2 Event and Status Management

Waste Production Event Architecture provides flexible event tracking that accommodates diverse material processing activities while maintaining standardised data structures and reporting capabilities.

Event records include status information, timestamps, location data, and activity-specific details stored in dedicated fields for common event types. This design balances query performance with flexibility while enabling comprehensive audit trails and operational reporting.

Transport event tracking captures vehicle information, route details, and timing data while maintaining relationships to organisations responsible for transportation activities. Processing event documentation includes treatment details, quality control information, and facility data that supports regulatory compliance and operational optimisation.

Status Management and Workflow Control implements state machine principles through status fields and timestamp tracking that ensure consistent material lifecycle progression while preventing invalid state transitions.

Status change auditing maintains comprehensive records of material condition changes while supporting automated workflow coordination and exception handling. Integration with user authentication provides accountability while supporting collaborative operations across organisational boundaries.

7.3.3 Supporting Infrastructure Tables

Authentication and Authorisation Framework implements comprehensive security infrastructure through RBAC (Role-Based Access Control) entities that support both application security and audit requirements.

User authentication integrates organisational membership with role assignments while supporting external system integration through API key management. Authorisation item hierarchy enables granular permission management while maintaining administrative efficiency through role-based assignments.

Localisation and Customisation Support accommodates multi-language operations and organisational customisation requirements through translation tables and configurable field definitions.

Message translation infrastructure supports user interface localisation while custom field definitions enable organisational adaptation without schema modifications. This design maintains system standardisation while accommodating diverse operational requirements and regulatory frameworks.

System Configuration and Metadata Management provides administrative infrastructure for system operation, including audit logging, performance monitoring, and operational configuration.

Migration tracking ensures consistent schema evolution while grid view customisation supports user experience optimisation. CMS integration enables content management while classification systems support flexible access control and data organisation.

7.4 Performance Optimisation and Indexing Strategy

Database performance optimisation incorporates indexing strategies, query optimisation, and scaling considerations that support efficient operations across growing data volumes and user bases.

7.4.1 Index Design and Query Optimisation

Primary and Composite Indexes optimize common query patterns, including material searches, status filtering, and timeline-based reporting, while maintaining insert performance for operational data entry.

Material tracking queries benefit from composite indexes on material type, status, and timestamp fields, while location-based searches utilise geographic indexes for spatial queries. User-specific data access patterns utilise indexes on organisational relationships and role assignments.

Query Performance Monitoring identifies optimisation opportunities through execution plan analysis and performance metrics collection. Slow query identification enables proactive optimisation while index usage statistics inform maintenance and tuning activities.

7.4.2 Scalability and Maintenance Considerations

Partitioning Strategies accommodate data growth through time-based partitioning for event tables and organisation-based partitioning for multi-tenant data segregation.

Archive and retention policies manage historical data volumes while maintaining regulatory compliance and audit trail requirements. Automated maintenance procedures optimise index performance and manage storage utilisation while preserving data integrity.

Backup and Recovery Architecture implements comprehensive data protection through automated backup procedures, point-in-time recovery capabilities, and disaster recovery planning that ensures business continuity while maintaining data security.

7.5 Data Integrity and Business Rules

Database-level constraints and business rules ensure data consistency while supporting application-level validation and workflow coordination.

7.5.1 Referential Integrity and Constraints

Foreign Key Relationships maintain data consistency across related entities while supporting appropriate cascade operations for record lifecycle management. Constraint design balances data integrity with operational flexibility while preventing orphaned records and invalid references.

Check Constraints and Validation enforce business rules at the database level, including status value validation, quantity range checking, and timestamp consistency verification. These constraints provide defensive data protection while supporting application-level validation frameworks.

7.5.2 Audit Trail and Change Management

Comprehensive Audit Logging tracks all data modifications, including user identification, timestamp information, and change details that support regulatory compliance and operational accountability.

Version control for critical entities maintains historical records while enabling change analysis and rollback capabilities. Audit trail integration with application security provides comprehensive accountability while supporting forensic analysis and compliance verification.

Data Governance and Compliance implementation includes data classification, retention policies, and privacy protection measures that ensure regulatory compliance while maintaining operational efficiency and user experience quality.

7.6 Database tables

The following tables explain fields with their related data types used in the Rebuilt Database.

7.6.1 `active_gridview_columns` database table

This table stores records of grid column configurations that are specific to both a particular user and a specific model. It allows each customer to define and display a custom set of columns in the grid view, so that different users can have their own preferred columns for each model based on their needs. Table 7 provides a detailed description of its fields

Table 7: `active_gridview_columns` fields

Field	Type	Comment
id	int(11) NOT NULL	
column_name	varchar(255) NOT NULL	
related_model	varchar(255) NULL	
model	varchar(255) NOT NULL	
customer_id	int(11) NULL	
order	smallint(6) NOT NULL	

7.6.2 `attachment` database table

This table contains references to files managed in the portal, including product images, documents, and other media. Each record stores information about the file path, name, optional description, and the model it is linked to. If applicable, it also includes the ID of the resource in CinderOss. Table 8 provides a detailed description of its fields.

Table 8: `attachment` fields

Field	Type	Comment
id	int(11) NOT NULL	
path	varchar(255) NOT NULL	
name	varchar(255) NOT NULL	
model	varchar(255) NULL	
model_id	int(11) NULL	
description	varchar(256) NULL	
cinder_resource_id	varchar(256) NULL	Id of image resource in CinderOss

7.6.3 `AuthAssignment` database table

This table stores assignments of RBAC security profiles to users. For example, a user can be assigned the "Manage" or "Operator" profile. Table 9 provides a detailed description of its fields.

Table 9: `AuthAssignment` fields

Field	**Type**	**Comment**
item_name	varchar(64) NOT NULL	
user_id	varchar(64) NOT NULL	
created_at	int(11) NULL	

7.6.4 `AuthItem` database table

This table contains a list of system functions, views, and forms that can be assigned to RBAC profiles. Each record represents a permission or role that can be linked to users via RBAC assignments, allowing fine-grained control over access to different parts of the application. Table 10 provides a detailed description of its fields.

Table 10: `AuthItem` fields

Field	Type	Comment
name	varchar(64) NOT NULL	
type	smallint(6) NOT NULL	
description	text NULL	
rule_name	varchar(64) NULL	
data	blob NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	

7.6.5 `AuthItemChild` database table

Stores the relationships between RBAC AuthItem entries in Yii. Each record defines a parent-child link, allowing hierarchical management of roles and permissions in the system. Table 11 provides a detailed description of its fields.

Table 11: `AuthItemChild` fields

Field	Type	Comment
parent	varchar(64) NOT NULL	
child	varchar(64) NOT NULL	

7.6.6 `AuthRule` database table

The AuthRule table stores rules for Yii's RBAC (Role-Based Access Control) system. It contains the rule name, serialised rule data, and timestamps for creation and last update. Rules are used to implement conditional access checks, for example, allowing actions only for certain users or under specific conditions. Table 12 provides a detailed description of its fields.

Table 12: `AuthRule` fields

Field	Type	Comment
name	varchar(64) NOT NULL	
data	blob NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	

7.6.7 `classification` database table

This table contains the classification of roles for access to product attachments (e.g., Public, B2B, Public Authority, Partners, Internal, Reserved, Secret) and is used to control the visibility of attachments based on user roles. Table 13 provides a detailed description of its fields.

Table 13: `classification` fields

Field	Type	Comment
id	int(11) NOT NULL	
name	varchar(64) NOT NULL	
role	varchar(64) NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	

7.6.8 `cms_page` database table

This table stores content for CMS pages. Each record can include the page title, content, type, and optional fields such as text, additional text, and WhatsApp-specific content. Pages can be categorized via the category field and optionally linked to a specific customer via customer_id. Table 14 provides a detailed description of its fields.

Table 14: `cms_page` fields

Field	Type	Comment
id	int(11) NOT NULL	
title	varchar(255) NOT NULL	
content	text NULL	
type	varchar(255) NOT NULL	
text	text NULL	
whatsapp_content	text NULL	
additional_text	text NULL	
category	int(3) NULL	
customer_id	int(11) NULL	

7.6.9 `custom_field` database table

This table is part of the **Custom Field** module, which allows managing personalized forms for products. It enables the creation of **custom data fields** for web forms and pages and **allows adding user-defined forms to arbitrary pages**. Field labels can be **translated** and **renamed** as needed to support different terms or languages. Table 15 provides a detailed description of its fields.

Table 15: `custom_field` fields

Field	Type	Comment
id	int(11) NOT NULL	
name	varchar(255) NULL	
data	text NULL	
type	tinyint(3) NULL	

7.6.10 `gridview_columns_classification_pivot` database table

Supporting pivot table for classification and fields of the specific models. This table helps to manage fields according to the user permissions and field classification. Table 16 provides a detailed description of its fields.

Table 16: `gridview_columns_classification_pivot` fields

Field	Type	Comment
id	int(11) NOT NULL	
column_name	varchar(255) NOT NULL	
model	varchar(255) NOT NULL	
classification_id	int(11) NOT NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	

7.6.11 `location` database table

This table stores all location data used in the portal. Table 17 provides a detailed description of its fields.

Table 17: `location` fields

Field	Type	Comment
id	int(11) NOT NULL	
description	varchar(255) NULL	
address	varchar(255) NULL	
city	varchar(255) NULL	
country	varchar(255) NULL	
latitude	decimal(9,6) NULL	
longitude	decimal(9,6) NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	

7.6.12 `message` database table

System table that contains translations in local languages of system strings stored in db table 'sourceMessage'. Actually, the supported languages are English, Italian, and Slovenian. Table 18 provides a detailed description of its fields.

Table 18: `message` fields

Field	Type	Comment
id	int(11) NOT NULL	
language	varchar(16) NOT NULL	
translation	text NULL	

7.6.13 `migration` database table

This table tracks database schema updates applied when the software is updated. Each record stores the migration version and the timestamp (apply time) when the migration was applied, ensuring that database changes are applied in the correct order. Table 19 provides a detailed description of its fields.

Table 19: `migration` fields

Field	Type	Comment
version	varchar(180) NOT NULL	
apply_time	int(11) NULL	

7.6.14 `model_translation` database table

Table that contains translations for different languages for entities (ex. Product). Table 20 provides a detailed description of its fields.

Table 20: `model_translation` fields

Field	Type	Comment
id	int(11) NOT NULL	
model_class	varchar(255) NOT NULL	

model_id	int(11) NULL	
language	varchar(16) NOT NULL	
attribute	varchar(255) NOT NULL	
value	text NOT NULL	

7.6.15 `organisation` database table

The database table holds a list of organisations authorised in the Rebuilt portal. Table 21 provides a detailed description of its fields.

Table 21: `organisation` fields

Field	Type	Comment
id	int(11) NOT NULL	
parent_id	int(11) NULL	
name	varchar(255) NOT NULL	
company_name	varchar(255) NULL	
vat_number	varchar(255) NULL	
tax_code	varchar(255) NULL	
administrative_email	varchar(255) NULL	
referent_email	varchar(255) NULL	
contact	varchar(255) NULL	
address	varchar(255) NULL	
city	varchar(255) NULL	

block_duplicate_email	int(11) NULL	
state	varchar(255) NULL	
telephone	varchar(255) NULL	
zip_code	varchar(255) NULL	
logo	varchar(255) NULL	
language	varchar(6) NULL	
country	varchar(255) NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	
supplier	tinyint(1) NULL	
transporter	tinyint(1) NULL	
recycling_company	tinyint(1) NULL	
demolishing_company	tinyint(1) NULL	

7.6.16 `organisation_location` database table

This is a pivot table that establishes a many-to-many relationship between the organisation and location tables. It is used to associate organisations with one or more locations, enabling flexible mapping of organisations to their physical or operational locations. Table 22 provides a detailed description of its fields.

Table 22: `organisation_location` fields

Field	Type	Comment
id	int(11) NOT NULL	
organisation_id	int(11) NOT NULL	
location_id	int(11) NOT NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	

7.6.17 `organisation_waste_type_pivot` database table

This is a pivot table that establishes a many-to-many relationship between the organisation and waste_type tables. It is used to associate organisations with one or more waste types, enabling flexible mapping of organisations to their waste types. Table 23 provides a detailed description of its fields.

Table 23: `organisation_waste_type_pivot` fields

Field	Type	Comment
id	int(11) NOT NULL	
organisation_id	int(11)	
waste_type	int(11)	

7.6.18 `product` database table

This table stores information about products available in the system. Table 24 provides a detailed description of its fields.

Table 24: `product` fields

Field	Type	Comment
id	int(11) NOT NULL	
name	varchar(128) NOT NULL	
description	text NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	
color	varchar(8) NULL	
weight_kg	decimal(5,2) NULL	
width	decimal(10,2) NULL	
height	decimal(10,2) NULL	
custom_fields	text NULL	
serial	varchar(40) NULL	
taric_id	int(11) NULL	
gtin_code	varchar(13) NULL	
synced_at	datetime NULL	
remote_id	varchar(255) NULL	
unique_product_id	varchar(64) NULL	
intended_use	varchar(64) NULL	
harmonised_standard	varchar(64) NULL	
dop_reference_number	varchar(64) NULL	
dop_date	date NULL	
system_assessment	varchar(64) NULL	
certification_body	varchar(64) NULL	
certification_number	varchar(64) NULL	

compressive_strength	decimal(5,1) NULL	
density	decimal(6,1) NULL	
fire_resistance_class	varchar(64) NULL	
thermal_conductivity	decimal(4,3) NULL	
safety_instructions_attached	tinyint(1) NULL	
recyclability_rate	int(11) NULL	
ghg_emissions	decimal(8,6) NULL	
recycled_content	int(11) NULL	
digital_carrier_type	varchar(64) NULL	
carrier_location	varchar(64) NULL	
data_access_url	varchar(255) NULL	
linked_eu_legislation	varchar(255) NULL	
safety_data_sheet_available	tinyint(1) NULL	
technical_file_reference	varchar(64) NULL	
dpp_create_by	int(11) NULL	
dpp_creation_date	date NULL	
dpp_last_updated	date NULL	
dpp_backup_location	varchar(255) NULL	
dpp_version_number	varchar(20) NULL	

7.6.19`product_attachment` database table

This table store files that were attached to the product (ex. Manual, Certificate, Material lab Analysis etc…). Table 25 provides a detailed description of its fields.

Table 25: `product_attachment` fields

Field	Type	Comment
id	int(11) NOT NULL	
product_id	int(11) NOT NULL	
product_attachment_type_id	int(11) NOT NULL	
description	text NULL	
ipr	varchar(32) NULL	
classification	int(11) NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	

7.6.20 `product_attachment_type` database table

This table stores types of attachments which are used in product attachment (ex. Certificate, Manual, etc). Table 26 provides a detailed description of its fields.

Table 26: `product_attachment_type` fields

Field	Type	Comment
id	int(11) NOT NULL	
name	varchar(32) NOT NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	

7.6.21`product_dpp_sign` database table

This table stores signed versions of a product's DPP (Digital Product Passport) after each modification. It includes a hash of the signed data, the full JSON representation of the DPP, and an optional blockchain ID for external verification. Table 27 provides a detailed description of its fields.

Table 27: `product_dpp_sign` fields

Field	Type	Comment
id	int(11) NOT NULL	
product_id	int(11) NOT NULL	
hash	text not NULL	
json	Json not NULL	
blockchain_id	varchar(64) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	

7.6.22`product_raw_material_pivot` database table

This table is a pivot table that establishes a many-to-many relationship between the product and raw material tables. It is used to associate each product with one or more raw materials, enabling flexible tracking of which materials are used in which products. Table 28 provides a detailed description of its fields.

Table 28: `product_raw_material_pivot` fields

Field	Type	Comment
id	int(11) NOT NULL	
product_id	int(11) NOT NULL	
raw_material_id	int(11) NOT NULL	
quantity	decimal(10,2) NULL	
unit	varchar(64) NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	

7.6.23 `raw_material` database table

This table stores information about raw materials produced during the waste disposal process. Table 29 provides a detailed description of its fields.

Table 29: `raw_material` fields

Field	Type	Comment
id	int(11) NOT NULL	
material_description	varchar(255) NULL	
quantity	decimal(10,0) NULL	
unit	varchar(64) NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	

7.6.24`raw_material_waste_disposal_pivot` database table

This table is a pivot table that creates a many-to-many relationship between raw_materials and waste_disposal records. It is used to track which raw materials were generated from specific waste disposal processes, enabling detailed traceability of material disposal. Table 30 provides a detailed description of its fields.

Table 30: `raw_material_waste_disposal_pivot` fields

Field	Type	Comment
id	int(11) NOT NULL	
raw_material_id	int(11) NOT NULL	
waste_disposal_item_id	int(11) NOT NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	

7.6.25`source_message` database table

In the Rebuilt Portal software, there is a part of its database named "source_message" where all the text used in the software (like instructions and buttons) is listed in English. When new features are added to this software, new pieces of text may be created. These texts can be translated into various languages supported by the Rebuild Portal. Once translated, these texts are stored in a different part of the database called "messages". This system ensures that the software can display its content in multiple languages, making it user-friendly for people from different language backgrounds. Table 31 provides a detailed description of its fields.

Table 31: `source_message` fields

Field	Type	Comment
id	int(11) NOT NULL	
category	varchar(255) NULL	
message	text NULL	

7.6.26`taric` database table

This table stores TARIC (Integrated Tariff of the European Communities) codes and related data. TARIC codes are used for classifying goods for customs, trade, and regulatory purposes. Table 32 provides a detailed description of its fields.

Table 32: `taric` fields

Field	Type	Comment
id	int(11) NOT NULL	
taric_code	varchar(10) NULL	
description	text NULL	
measure_type	varchar(255) NULL	
duty_rate	decimal(5,2) NULL	
country_of_origin	varchar(2) NULL	
start_date	date NULL	
end_date	date NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	

7.6.27`top_menu` database table

This table stores internal and external links displayed as clickable buttons in the portal's header navigation menu, providing quick access to portal sections and external resources. Table 33 provides a detailed description of its fields. Table 33 provides a detailed description of its fields.

Table 33: `top_menu` fields

Field	Type	Comment
id	int(11) NOT NULL	
title	varchar(255) NOT NULL	
url	varchar(255) NOT NULL	
order	smallint(6) NOT NULL	
organisation_id	int(11) NOT NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	

7.6.28`user` database table

This table stores a list of active system users for both the Rebuilt Portal. In addition to a password, each user is assigned an authentication key (auth_key), which is utilised for verifying their identity through the RestAPI using a bearer token. Table 34 provides a detailed description of its fields.

Table 34: `user` fields

Field	Type	Comment
id	int(11) NOT NULL	
organisation_id	int(11) NULL	

name	varchar(255) NOT NULL	
surname	varchar(255) NOT NULL	
email	varchar(255) NOT NULL	
auth_key	varchar(32) NOT NULL	
password_hash	varchar(255) NOT NULL	
password_reset_token	varchar(255) NULL	
verification_token	varchar(255) NULL	
language	varchar(6) NULL	
status	smallint(6) NOT NULL	
token	varchar(32) NULL	
logo	varchar(255) NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	

7.6.29`waste_disposal` database table

The database table stores information about the waste production process. Table 35 provides a detailed description of its fields.

Table 35: `waste_disposal` fields

Field	Type	Comment
id	int(11) NOT NULL	
description	varchar(255) NULL	
disposal_datetime	datetime NULL	
disposal_no	int(11) NULL	
user_id	int(11) NOT NULL	
location_departure	int(11) NOT NULL	
organisation_supplier	int(11) NOT NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	
reference_no	varchar(64) NULL	
demolishing_org_id	int(11) NULL	
waste_management_plan_id	varchar(64) NULL	
construction_permit_number	varchar(64) NULL	
location_of_construct_proj	int(11) NULL	
wp_evidence_sheet_ref	varchar(64) NULL	

7.6.30`waste_disposal_item` database table

This table stores detailed records of waste produced items associated with a waste production process. It provides granular tracking and reporting of waste materials processed or disposed of. Table 36 provides a detailed description of its fields.

Table 36: `waste_disposal_item` fields

Field	Type	Comment
id	int(11) NOT NULL	
waste_type_id	int(11) NOT NULL	
waste_disposal_id	int(11) NOT NULL	
quantity	decimal(10,0) NULL	
unit	varchar(255) NULL	
user_id	int(11) NOT NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	
waste_batch_id	varchar(64) NULL	

7.6.31`waste_production_event` database table

This table stores detailed records of all transport and processing events related to waste processing items (waste_disposal_item table). Table 37 provides a detailed description of its fields.

Table 37: `waste_production_event` fields

Field	Type	Comment
id	int(11) NOT NULL	
status	varchar(16) NULL	
status_changed_at	datetime NULL	
wdi_id	int(11) NULL	
arrival_time	datetime NULL	
departure_time	datetime NULL	
extra_info	text NULL	
transport_evidence_sheet	varchar(64) NULL	
vehicle_type	varchar(16) NULL	
consumed_transport_event_id	varchar(64) NULL	
hazardous	varchar(255) NULL	
non_hazardous	varchar(255) NULL	
processing_id	varchar(64) NULL	
processor_permit_issued_at	date NULL	
processor_permit_no	varchar(64) NULL	
storage_location	int(11) NULL	

treated_mass_t	decimal(12,3) NULL	
treatment_location	int(11) NULL	
treatment_type	varchar(255) NULL	
location_departure	int(11) NULL	
location_destination	int(11) NULL	
transport_org_id	int(11) NULL	
recycling_org_id	int(11) NULL	

7.6.32`waste_type` database table

This table stores waste type codes based on the EU waste classification system. Table 38 provides a detailed description of its fields.

Table 38: `waste_type` fields

Field	Type	Comment
id	int(11) NOT NULL	
description	varchar(255) NULL	
code	varchar(64) NULL	
code2	varchar(64) NULL	
code3	varchar(64) NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	
waste_type_category_id	int(11) NULL	
ewc	varchar(64) NULL	
y_code	varchar(64) NULL	

7.6.33`waste_type_category` database table

This table stores waste type categories for group codes based on the EU waste classification system. Table 39 provides a detailed description of its fields

Table 39: `waste_type_category` fields

Field	Type	Comment
id	int(11) NOT NULL	
description	varchar(255) NULL	
active	tinyint(1) NULL	
deleted	tinyint(1) NULL	
created_at	int(11) NULL	
updated_at	int(11) NULL	

8 Challenges and Lessons Learned

The development and implementation of the digital material traceability platform at the NIGRAD demonstration centre provided valuable insights into the practical challenges of deploying circular economy technologies in construction industry contexts. This chapter documents the significant obstacles encountered, solutions developed, and strategic lessons that inform future implementations and scaling strategies.

8.1 Technical Implementation Challenges

The complexity of integrating diverse technological components while maintaining system reliability and user experience presented several significant technical challenges that required innovative solutions and architectural adaptations.

8.1.1 System Integration Complexity

Multi-System Interoperability proved more challenging than initially anticipated, particularly when integrating with legacy construction industry systems that often lack modern API capabilities or standardized data formats. BIM system integration required extensive custom development to accommodate varying IFC implementation standards across different software platforms, while marketplace connectivity demanded flexible data transformation capabilities to support diverse partner requirements.

The solution involved developing a comprehensive integration layer with standardised internal data formats and flexible transformation engines that could accommodate varying external system requirements. This approach required additional development time but provided a robust foundation for future integration expansions.

External System Dependencies created reliability challenges when third-party systems experienced outages or performance degradation. Gaia-X infrastructure integration, while strategically important, required careful implementation of fallback procedures and offline operation modes to maintain platform functionality during external system unavailability.

Implementing comprehensive error handling, retry mechanisms, and graceful degradation procedures proved essential for maintaining user productivity while external systems were restored. Local caching and offline operation capabilities became critical features rather than optional enhancements.

8.1.2 Performance and Scalability Optimisation

Database Performance Under Load emerged as a significant concern as material tracking data volumes grew and user concurrency increased during pilot operations. Complex queries involving material lifecycle tracking and audit trail generation required extensive optimisation to maintain acceptable response times.

Strategic database indexing, query optimisation, and selective denormalisation for reporting functions addressed immediate performance concerns while establishing foundations for horizontal scaling. However, this required more intensive database administration effort than initially planned.

Mobile Application Synchronisation presented unique challenges in construction site environments where network connectivity is often intermittent or unreliable. Offline operation capabilities required careful design of data conflict resolution and synchronisation procedures that maintained data integrity while providing responsive user experiences.

The final solution implemented optimistic conflict resolution with manual override capabilities for complex conflicts, while automatic synchronisation handled the majority of routine data updates seamlessly.

8.2 Operational and User Adoption Challenges

Transitioning from traditional paper-based material tracking to comprehensive digital systems required addressing significant organisational change management and user training challenges.

8.2.1 User Training and Change Management

Digital Literacy Variations among construction industry workers created significant training challenges, as users ranged from highly tech-savvy project managers to field workers with limited digital system experience. Standard training approaches proved insufficient for accommodating this diverse user base.

Developing role-specific training programs with hands-on practice sessions and peer mentoring proved more effective than traditional classroom training. However, this required substantially more training time and resources than initially budgeted, extending implementation timelines and increasing deployment costs.

Workflow Integration Resistance emerged from established operational procedures and concerns about productivity impacts during transition periods. Workers accustomed to paper-based systems initially viewed digital requirements as additional bureaucracy rather than efficiency improvements.

Demonstrating clear productivity benefits through pilot implementations and providing immediate feedback on time savings helped overcome resistance. However, achieving full adoption required sustained management support and continuous user experience optimisation based on field feedback.

8.2.2 Data Quality and Consistency Management

Inconsistent Data Entry practices across different users and organisations created data quality challenges that affected reporting accuracy and system reliability. Variations in material classification, condition assessment, and documentation standards required extensive data cleaning and validation procedures.

Implementing comprehensive data validation rules, standardised dropdown selections, and guided data entry workflows improved consistency significantly. However, balancing data standardisation with operational flexibility required careful design iteration based on user feedback.

Historical Data Migration from existing paper records and legacy digital systems proved more complex than anticipated, requiring extensive manual verification and data cleaning procedures. Incomplete or inconsistent historical records created gaps in material provenance tracking that affected circular economy impact calculations.

8.3 Regulatory and Compliance Challenges

Navigating evolving regulatory frameworks while maintaining operational efficiency presented ongoing challenges throughout the implementation process.

8.3.1 Regulatory Framework Evolution

Dynamic Compliance Requirements changed during the implementation period as European Union Digital Product Passport regulations evolved and Gaia-X standards matured. Maintaining compliance while avoiding over-engineering for uncertain future requirements required careful balance.

Implementing flexible configuration systems and modular compliance modules enabled adaptation to regulatory changes without fundamental system redesign. However, this approach required additional development resources and ongoing monitoring of regulatory developments.

Cross-Border Data Sharing Regulations created complexity when implementing Gaia-X integration, as different member states had varying interpretations of data sovereignty and privacy requirements. Ensuring compliance across multiple jurisdictions while maintaining operational efficiency required extensive legal consultation.

8.3.2 Data Protection and Privacy Implementation

GDPR Compliance Integration required more comprehensive implementation than initially anticipated, particularly regarding consent management for third-party data sharing and individual privacy rights in business-to-business contexts.

Implementing comprehensive data classification, automated retention policies, and user consent management systems addressed compliance requirements but required significant additional development effort and ongoing administrative overhead.

8.4 Economic and Business Model Challenges

Demonstrating clear economic value while managing implementation costs presented ongoing challenges that influenced platform design and deployment strategies.

8.4.1 Return on Investment Demonstration

Quantifying Circular Economy Benefits proved difficult due to the complexity of measuring environmental impact reductions and economic value creation from material reuse activities. Traditional cost-benefit analysis methods were insufficient for capturing long-term sustainability benefits.

Developing comprehensive metrics frameworks that captured both direct operational benefits and indirect sustainability value required collaboration with environmental economists and life-cycle assessment specialists. This provided more compelling business cases but required additional analytical resources.

Implementation Cost Management exceeded initial estimates due to the complexity of integration requirements and extended training needs. Hardware costs for RFID readers and mobile devices, combined with ongoing system administration requirements, created budget pressures for smaller organisations.

8.4.2 Market Development and Adoption

Limited Market Liquidity for circular economy materials created challenges in demonstrating platform value through successful material transactions. Building sufficient material supplier and buyer participation required extensive relationship development and market-making activities beyond pure technology deployment.

Successful market development required combining technology deployment with business development activities, education programs, and policy advocacy that extended beyond the original project scope.

8.5 Strategic Lessons Learned

The implementation experience provided valuable insights that inform future development priorities and deployment strategies for similar initiatives.

8.5.1 Technology Architecture Insights

Modular Design Importance proved critical for managing implementation complexity and accommodating evolving requirements. Systems designed with clear separation between core functionality and integration modules adapted more successfully to changing external requirements and user feedback.

User Experience Prioritisation emerged as more critical than initially recognised, particularly for field applications where user productivity directly impacts adoption success. Investing in user experience design and iterative improvement based on real usage patterns proved more valuable than adding advanced features.

Integration Strategy Evolution demonstrated that comprehensive external system integration should be implemented gradually rather than simultaneously. Phased integration approaches enabled better testing, user training, and issue resolution while maintaining system stability.

8.5.2 Implementation and Change Management Insights

Stakeholder Engagement Depth required more intensive and sustained effort than traditional software implementations. Construction industry stakeholders needed extensive education about circular economy concepts in addition to system training, requiring broader change management approaches.

Organisational Readiness Assessment became critical for successful deployments. Organisations with existing digital systems and change management capabilities adopted the platform more successfully than those requiring simultaneous digital transformation and process redesign.

Pilot Implementation Value demonstrated the importance of controlled testing environments for identifying issues and optimising procedures before broader deployment. The NIGRAD demonstration centre provided invaluable learning opportunities that informed system improvements and training program development.

8.5.3 Market and Policy Development Insights

Policy Integration Necessity became clear as purely technological solutions proved insufficient for driving broad market adoption. Successful circular economy transformation requires coordinated policy support, market incentives, and technology deployment.

Industry Collaboration Requirements exceeded expectations as material tracking effectiveness depended on participation across entire value chains rather than individual organisational implementations. Network effects became critical for platform value creation.

Long-Term Sustainability Planning emerged as essential for maintaining platform value as initial project funding concluded. Developing sustainable business models and ongoing support structures proved as important as initial technical implementation.

8.6 Recommendations for Future Implementations

Based on implementation experience and lessons learned, several strategic recommendations emerge for organisations considering similar digital circular economy initiatives.

8.6.1 Implementation Strategy Recommendations

Phased Deployment Approach should prioritise core material tracking functionality before implementing advanced integration features. This enables users to gain familiarity with basic concepts while providing immediate operational value before advancing to complex features.

Comprehensive Training Investment should include circular economy education in addition to system training, as user understanding of sustainability concepts directly impacts engagement and adoption success.

Stakeholder Ecosystem Development requires coordinated outreach across supply chains rather than focusing solely on direct users. Platform value depends on network participation that extends beyond individual organisational boundaries.

8.6.2 Technical Development Recommendations

User Experience Optimisation should receive priority throughout development rather than being addressed after core functionality implementation. Field usability requirements often conflict with comprehensive functionality, requiring careful balance and iterative design.

Integration Architecture Planning should anticipate future requirements while avoiding over-engineering for uncertain specifications. Modular designs with clear interface definitions enable adaptation while maintaining development efficiency.

Performance Planning Early in development cycles prevents costly optimisation requirements during deployment phases. Database design, caching strategies, and mobile synchronisation approaches should be validated under realistic load conditions before production deployment.

The challenges encountered and lessons learned during this implementation provide valuable guidance for future digital circular economy initiatives while demonstrating both the potential and complexity of comprehensive material traceability systems in construction industry contexts.

9 Conclusions and Next Steps

The successful implementation and validation of INFORDATA SISTEMI's digital material traceability platform at the NIGRAD demonstration centre establishes a significant milestone in construction industry circular economy transformation. This final chapter synthesises key achievements, assesses strategic implications, and outlines concrete pathways for scaling impact across European construction markets.

9.1 Key Achievements and Technical Validation

The platform implementation demonstrates that comprehensive digital material traceability is both technically feasible and operationally viable within real construction industry contexts. The integration of RFID identification, cloud-based data management, Digital Product Passports, and external system connectivity creates a functional ecosystem that addresses previously fragmented material tracking requirements.

Technical Architecture Success validates the modular, API-first design approach that enables independent scaling of different system components while maintaining data integrity and security across all operational layers. The Yii2-based web application architecture provides enterprise-grade reliability, while the MySQL database schema accommodates complex material relationships and audit trail requirements without performance degradation.

Integration Capabilities Demonstration confirms that construction industry systems can effectively connect with broader European digital infrastructure through Gaia-X compliance, BIM system compatibility, and marketplace integration. The successful implementation of Digital Product Passports with cryptographic signing provides a foundation for regulatory compliance while supporting automated verification across organisational boundaries.

User Experience Validation at NIGRAD confirms that field workers, material processors, and administrative users can effectively operate digital tracking systems when provided with appropriate training and interface design. Mobile application functionality enables real-time data collection under construction site conditions while web-based management interfaces support comprehensive material lifecycle coordination.

9.2 Business Value and Impact Assessment

The pilot implementation provides empirical evidence of measurable benefits across operational efficiency, regulatory compliance, and circular economy impact dimensions that justify continued investment and scaling efforts.

Operational Efficiency Improvements include streamlined material documentation processes, automated regulatory reporting generation, and enhanced inventory management capabilities that reduce administrative overhead while improving data accuracy. Real-time material status tracking enables optimised storage utilisation and more efficient procurement coordination across multiple organisations.

Regulatory Compliance Enhancement demonstrates automated generation of waste tracking documentation, transportation manifests, and circular economy performance reports that reduce compliance costs while improving accuracy and audit trail comprehensiveness. Integration with emerging Digital Product Passport requirements positions early adopters for regulatory compliance advantages.

Circular Economy Impact Quantification enables measurement of material reuse percentages, waste diversion rates, and environmental impact reductions that support sustainability reporting and policy development. The platform's capability to track materials through complete lifecycles provides previously unavailable data for optimizing circular economy strategies and demonstrating environmental benefits.

Market Development Facilitation through integrated marketplace connectivity creates new revenue opportunities for material suppliers while providing construction projects with expanded access to circular economy materials. Digital documentation and quality verification reduce transaction costs and buyer risk, improving market liquidity for secondary materials.

9.3 Strategic Implications for Construction Industry Transformation

The successful pilot implementation demonstrates broader strategic implications for construction industry digitalisation and circular economy adoption across European markets.

Digital Infrastructure Readiness confirms that construction industry organisations can successfully implement comprehensive digital tracking systems when provided with appropriate technology solutions, training programs, and change management support. The platform's demonstrated compatibility with existing BIM workflows and regulatory frameworks reduces adoption barriers for mainstream construction companies.

Policy Framework Alignment validates the technical feasibility of comprehensive material documentation requirements being considered in EU circular economy legislation. The platform's demonstrated capabilities support policy development while providing implementation experience that informs realistic regulatory timelines and requirements.

Market Transformation Potential shows that digital platforms can create economic incentives for circular economy practices by reducing transaction costs, improving quality verification, and enabling efficient material matching across geographic and organisational boundaries. Network effects become apparent as platform value increases with broader adoption across construction value chains.

Technology Transfer Opportunities emerge from the successful integration of RFID tracking, cloud computing, and federated data sharing technologies in construction contexts. The platform architecture provides a template for similar implementations while demonstrating best practices for addressing industry-specific requirements.

9.4 Lessons for Scaling and Replication

Implementation experience provides strategic insights that inform broader adoption planning and technology transfer to additional regions and market segments.

Phased Implementation Strategy proves most effective for managing adoption complexity while demonstrating value to stakeholders. Beginning with core material tracking functionality before implementing advanced integration features enables users to gain familiarity while providing immediate operational benefits.

Stakeholder Ecosystem Development requires coordinated engagement across construction value chains rather than focusing solely on individual organisational implementations. Platform value depends on network participation that extends beyond direct users to include material suppliers, processors, transporters, and end users.

Training and Change Management Investment significantly affects adoption success and require sustained commitment beyond initial system deployment. Construction industry workers need education about circular economy concepts in addition to system training, requiring comprehensive change management approaches.

Integration Architecture Planning should anticipate future requirements while avoiding over-engineering for uncertain specifications. Modular designs with clear interface definitions enable adaptation to evolving regulatory requirements and external system changes while maintaining development efficiency.

9.5 Immediate Next Steps and Short-Term Priorities

Building on pilot implementation success, several immediate development and deployment priorities emerge for maximising platform impact and preparing for broader adoption.

9.5.1 Platform Enhancement and Optimisation

Performance Optimisation Initiative should address database query performance, mobile application responsiveness, and external system integration reliability based on operational usage patterns identified during pilot testing. Implementing advanced caching strategies, query optimisation, and connection pooling will support expanded user bases and material volumes.

User Experience Refinement based on NIGRAD user feedback should prioritise mobile interface optimisation, workflow streamlining, and training material development that accelerates user adoption and reduces support requirements. Field usability improvements directly impact productivity and adoption success.

Advanced Analytics Development should implement predictive analytics for material demand forecasting, processing optimisation, and market trend analysis that provide strategic decision support for material processors and construction companies. Machine learning capabilities can optimise material matching and reuse recommendations.

9.5.2 Market Expansion and Partnership Development

Regional Deployment Planning should identify target markets for platform replication while developing partnerships with construction companies, waste management operators, and regulatory authorities that support coordinated adoption efforts. Central European markets with existing circular economy initiatives provide logical expansion targets.

Strategic Partnership Development with BIM software vendors, construction management platform providers, and regulatory technology companies can accelerate integration capabilities while reducing development costs through shared standards and collaborative development approaches.

Pilot Site Expansion beyond NIGRAD to additional demonstration centres and commercial operations will provide broader validation while generating case studies and best practices that support marketing and adoption efforts.

9.6 Medium-Term Development Roadmap

Medium-term development priorities focus on advanced features, broader integration capabilities, and market-scale deployment preparation that position the platform for comprehensive construction industry adoption.

9.6.1 Advanced Technology Integration

Artificial Intelligence Implementation should develop computer vision capabilities for automated material condition assessment, natural language processing for document analysis, and predictive analytics for optimizing material processing and reuse decisions. AI capabilities can significantly improve operational efficiency while reducing manual assessment requirements.

Blockchain Integration Development should implement distributed ledger capabilities for immutable material provenance records, smart contracts for automated material transactions, and cryptocurrency

payments for circular economy incentives. Blockchain integration supports trust and transparency while enabling innovative business models.

IoT Sensor Integration should expand beyond RFID tracking to include environmental monitoring, structural health assessment, and automated material handling that provide comprehensive material status information while reducing manual intervention requirements.

9.6.2 Regulatory Compliance and Standards Development

Digital Product Passport Enhancement should align with evolving EU regulations while developing standardised schemas, verification procedures, and interoperability protocols that support cross-border material transactions and regulatory compliance.

Industry Standards Participation through collaboration with CEN, ISO, and industry associations can influence standards development while ensuring platform compliance with emerging requirements for digital construction and circular economy systems.

Certification and Accreditation Development should pursue relevant quality management, environmental management, and data security certifications that support enterprise adoption while demonstrating compliance with industry and regulatory requirements.

9.7 Long-Term Vision and Strategic Objectives

Long-term platform development aims to establish comprehensive digital infrastructure for the European construction industry circular economy transformation while supporting policy objectives and market development.

9.7.1 European-Scale Deployment

EU-Wide Platform Federation should develop capabilities for cross-border material tracking, harmonized regulatory compliance, and unified marketplace access that support single-market operations while respecting national sovereignty and regulatory frameworks.

Policy Integration and Influence should position the platform as a reference implementation for EU circular economy legislation while providing technical expertise for policy development and regulatory framework optimisation.

Market Infrastructure Development should support creation of liquid secondary material markets through standardised quality assessment, automated matching algorithms, and integrated financial services that reduce transaction costs while improving market efficiency.

9.7.2 Technology Leadership and Innovation

Research and Development Collaboration with European universities, research institutes, and technology companies should advance material tracking technologies, circular economy methodologies, and digital infrastructure capabilities that maintain competitive advantages while supporting industry transformation.

Open Source Community Development around core platform components should encourage broader adoption while creating collaborative development opportunities that accelerate innovation and reduce implementation costs for smaller organisations.

Intellectual Property Strategy should balance open collaboration with competitive advantages through strategic patent applications, trademark protection, and licensing approaches that support sustainable business models while encouraging industry adoption.

9.8 Success Metrics and Evaluation Framework

Measuring long-term success requires comprehensive metrics that capture operational performance, environmental impact, and market transformation outcomes across multiple dimensions and timeframes.

Operational Performance Indicators include material processing volumes, user adoption rates, system uptime statistics, and cost-per-transaction metrics that demonstrate platform efficiency and scalability while informing optimisation priorities.

Environmental Impact Metrics track material reuse percentages, waste diversion achievements, carbon footprint reductions, and resource efficiency improvements that quantify circular economy benefits while supporting sustainability reporting and policy evaluation.

Market Development Indicators measure transaction volumes, geographic coverage, participant diversity, and price discovery efficiency that demonstrate market transformation progress while identifying development opportunities and barriers.

Strategic Success Measures assess regulatory compliance achievements, technology transfer success, partnership development outcomes, and competitive positioning that indicate long-term sustainability and growth potential.

The successful implementation of this digital material traceability platform establishes a foundation for construction industry transformation while demonstrating the technical feasibility, economic viability, and strategic value of comprehensive circular economy solutions. The pathway forward requires sustained commitment to technology development, stakeholder engagement, and market cultivation that can achieve the vision of fully digitalised, circular construction markets across Europe.