# WP3-A2. Comparative study of information technologies applied to waste management at international level in stone sector.



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# 1. INTRODUCTION

This report presents the results of WP3-A2, Comparative study of information technologies applied to waste management at international level in stone sector.

The main objective is to analyse how digital tools are being incorporated into waste management processes and what impact they have on the sustainability and competitiveness of the sector. This analysis is an essential part of the RockChain project, which aims to transform stone waste management through innovative solutions such as Blockchain, the Internet of Things (IoT), and Big Data analysis.

Based on case studies from Spain, Germany, Croatia, and Romania, the document provides a clear overview of current national approaches. It also highlights opportunities for collaboration that could lay the foundations for a common European strategy, thus overcoming existing fragmentation and moving towards a unified digital framework.

The results obtained make it possible to define best practices and formulate strategic recommendations aimed at actors in the sector, public policy makers, and educational centres, with the aim of promoting the dual digital and ecological transition promoted by the European Union.

# 2. WASTE MANAGEMENT AND DIGITALISATION: AN OVERVIEW

Throughout the entire natural stone value chain in Europe, from extraction and cutting to polishing and finishing, waste generation is a constant at every stage. Traditionally, waste management focused on storing or disposing of waste safely. However, today the approach has changed: the aim is now to measure, classify, and track these materials in near real time, with the intention of reusing them as secondary raw materials, for example, replacing aggregates or binders in construction.

This change is in line with European priorities on the circular economy and data sharing. There are an increasing number of technical studies supporting this new approach: if the mineral composition and particle size are precisely controlled, sludge and stone rubble can effectively replace primary materials in mortars, concretes, and other products (EEA, 2021; European Parliament, 2024).

Digitization is the key tool that makes this transformation possible. Thanks to various integrated technologies, physical waste is converted into useful and manageable data:

- IoT and sensors: These allow continuous recording of fill level, weight, and moisture in silos and containers.
- Computer vision and artificial intelligence: These use cameras to automatically classify materials.
- Drones (UAVs): These perform volumetric scans of stockpiles using photogrammetry or LiDAR.
- Traceability: Physical batches are linked to digital records using QR codes, RFID tags, or soon, the Digital Product Passport (DPP).


*Figure 1: Digital Product Passport.*

Adopting common key performance indicators (KPIs), such as waste-to-product ratio, energy intensity (kWh/t), carbon footprint ($CO_2e/t$), and treatment cost (€/t), enables companies to measure their progress and support their sustainability efforts with data (EEA, 2021; Voukkali et al., 2023).

## 2.1. Waste management in the stone industry

Throughout the natural stone value chain, three main types of waste are generated: cutting and polishing sludge (a mixture of water and fine stone particles), solid fragments, and mineral dust. This waste represents a considerable volume at the European level. In 2022, for example, construction activities generated around 38.4% of total waste in the EU-27, while mining and quarrying contributed another 22.7% (Eurostat, 2024). For this reason, sectors linked to the handling of minerals and aggregates are key to current circular economy and traceability strategies.

Beyond safe disposal, numerous studies have shown that both sludge and solid waste can be used as partial substitutes in construction materials, such as mortars, base layers, or innovative binders. However, for these solutions to be implemented on an industrial scale, it is essential that certain properties (such as mineral composition, particle size distribution, and processing conditions) remain within specific ranges. In this regard, the standardization of characterization methods is a key step in moving from successful laboratory testing to actual market adoption (Afonso et al., 2023; Gehlot & Shrivastava, 2023).

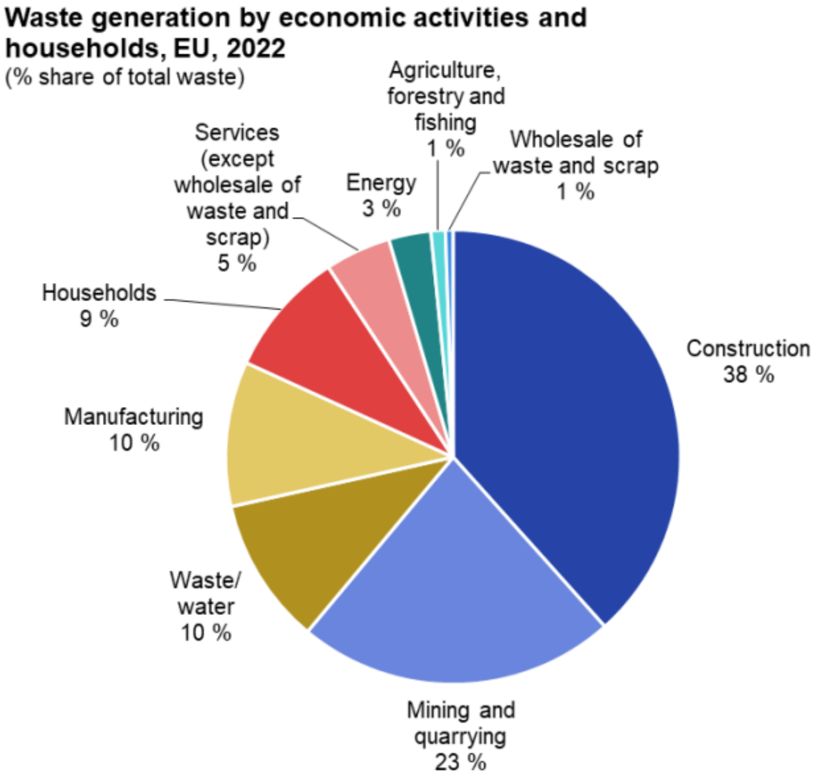


*Figure 2: Waste generation by economic activities and households, 2022.*

In this context, modern waste management requires clear indicators and up-to-date data on available volumes and flows. Among the most relevant indicators for evaluating performance are:

- Efficiency in the use of materials: tons of waste per ton of finished product.
- Energy intensity: energy consumption per ton produced (kWh/t).
- Environmental footprint: greenhouse gas emissions per ton ($CO_2e$/t).
- Cost efficiency: cost per ton treated (€/t).

Constant monitoring of these indicators allows companies to detect inefficiencies and plan logistics and recovery strategies more accurately, based on concrete data rather than estimates (EEA, 2021).

## 2.2. Digital transformation in waste management

Digitization is radically transforming the way waste is managed in processing plants and quarries. The traditional model, based on reactive interventions—for example, acting only when containers are full or problems arise—is giving way to proactive management, guided by real-time data. This provides up-to-date inventories and auditable data on material quality.

This change in approach involves treating sludge and debris not as undifferentiated waste, but as managed materials with defined characteristics: origin, moisture content, particle size, and volume. Continuous measurement and traceability facilitate more accurate planning, reduce energy consumption per ton, and optimize logistics. In addition, shared data dashboards provide customers and authorities with a transparent and verifiable view of performance (Berg et al., 2020; EEA, 2021).

In the natural stone sector, this digital transformation is based on four strategic pillars:

- Volumetric monitoring of stockpiles: Drones equipped with cameras or laser scanners perform automated flights over stockpiles. Using techniques such as photogrammetry or LiDAR scanning, the images are converted into 3D point clouds. If ground control points (GCPs) or RTK GPS are used, it is possible to calculate volumes with high accuracy. According to various studies, these estimates have margins of error like those of terrestrial scanners, typically between 1% and 6%, which is sufficient for daily inventory management and safety margins (Alsayed et al., 2023; Kokamägi et al., 2020; Kovanič et al., 2023).
- Dynamic routes and smart collection: IoT sensors installed in containers and vehicles measure key variables such as fill level, weight, or vibrations and send the data to a central platform. Instead of following fixed routes, algorithms prioritize collection based on capacity reached or load utilization per trip. This model, already tested in smart cities, significantly reduces collection routes and times and can be directly applied in quarry contexts (Khan et al., 2024).
- Digital labelling of fractions: Each batch of sludge or debris is registered as a "data object." Physical identifiers, such as QR codes on bags or RFID tags on pallets, link the material to its digital twin, which includes information about its origin (line, shift), physical properties (moisture content, particle size distribution), and prior treatment. By integrating with ERP or MES systems, automatic quality controls can be activated, such as blocking batches that exceed certain moisture levels until they are reconditioned, which also facilitates external audits (Berg et al., 2020; EEA, 2021).
- Data interoperability (Digital Product Passport): As rock by-products enter the construction materials market, buyers demand verifiable and easily shareable information. The European Digital Product Passport (DPP) initiative provides a standardized framework for exchanging data on composition, testing, and environmental footprint. Adopting these data models prepares the sector for future regulatory and green public procurement requirements (EPRS, 2024; Wan et al., 2025).

The sector is evolving from a waste management approach to true materials management. Even with minimal digital infrastructure (such as the use of drones for inventory, sensors for logistics, and interoperable batch data) concrete benefits are already being seen in costs, energy consumption, and emissions per ton, in addition to generating greater confidence in secondary materials of stone origin (Alsayed et al., 2023; EEA, 2024; Khan et al., 2024).

## 2.3. Key information technologies applied

In the natural stone sector, Information and Communication Technologies (ICT) are not a complement, but rather the operational basis that allows waste to be transformed into measurable, traceable, and constantly improving flows.

These digital tools work together to achieve three key objectives:

- Visibility: Knowing exactly how, where, and when sludge and debris are generated.
- Optimization: Improving logistics and treatment processes, from collection and conditioning to reuse or sale.
- Regulatory compliance: Documenting compliance with environmental regulations and quality requirements for secondary materials.

On a day-to-day basis, digital rock waste management combines several technologies: waste tracking systems, smart containers with remote monitoring, artificial intelligence-assisted sorting, mobile applications for field reporting, and traceability solutions such as RFID tags, QR codes, or blockchain-based records (Berg et al., 2020; EEA, 2021).

### 2.3.1. Waste tracking systems and traceability

Waste tracking systems leverage ICT to monitor the entire life cycle of stone waste: from its generation in cutting or polishing lines, through intermediate storage and transport, to its recovery or final disposal.

- Process monitoring: In quarries or processing plants, tracking begins with sensors and instruments installed on key equipment (such as saws, polishing lines, filter presses, or silos) that record the volumes generated and relevant parameters such as moisture content or material composition. This information is centralized on digital platforms that allow for the analysis of patterns in quantity and quality, facilitating planning based on real data.
- Digital identification and transportation: To link each physical batch to its digital record, identifiers such as barcodes, QR codes, or RFID tags are placed on containers, bags, or pallets. These codes are scanned at each stage of the process (drying, mixing, loading) reducing manual errors and creating a verifiable history. If it is also integrated with geolocation systems (GIS and GPS in trucks), the

logistics route can be monitored to ensure that materials reach their authorized destination.

- Integration with management systems: In more advanced configurations, tracking modules connect directly to enterprise resource planning (ERP) or production management systems. This allows production orders to be aligned with waste flows, accurate performance indicators to be generated, regulatory reports to be automated, and verification that by-products sent to third parties comply with agreed specifications.


*Figure 3: Waste tracking.*

### 2.3.2. Smart containers, remote monitoring and IoT

Smart containers and silos: These containers, although conventional in appearance, are equipped with industrial sensors (such as ultrasonic level detectors, load cells, or gas sensors) as well as communication modules. In the stone industry, this technology is key to managing slurry tanks, fines silos, and debris containers. The devices send real-time data on fill level, weight, or other anomalies (such as leaks or overheating) to a central platform. This visibility allows collections to be scheduled according to the actual capacity of the tanks, avoiding unnecessary trips with half-empty trucks and significantly reducing the risk of hazardous spills (Berg et al., 2020; Khan et al., 2024).

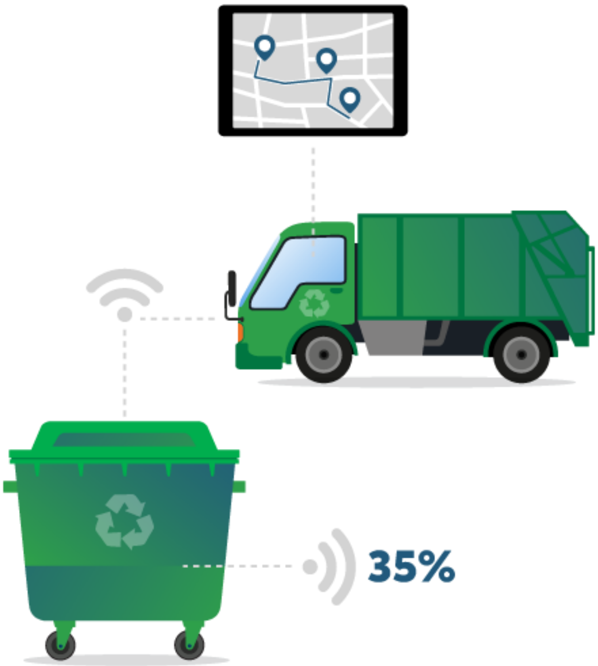


*Figure 4: Smart containers.*

Industrial remote monitoring: The Internet of Things (IoT) is not limited to storage. It can also be applied to monitoring active machinery in waste management. Key equipment such as slurry pumps, filter presses, or conveyor belts can incorporate sensors to measure vibration, temperature, pressure, or energy consumption. The system issues alerts if any operating parameters deviate from normal or if, for example, a container remains full for too long. This enables predictive maintenance and prevents failures before they occur. In more advanced implementations, field personnel use mobile applications that suggest optimized routes and allow tasks to be confirmed in real time, thus closing the loop between digital planning and physical operation (Kabugo et al., 2020; Khan et al., 2024).

#### 2.3.3. Artificial Intelligence (AI) and automated sorting

Artificial intelligence (AI) is revolutionizing rock waste management through two main applications: automatic material sorting and process optimization based on data analysis.

Computer vision and automatic sorting: Vision systems, which typically use RGB or hyperspectral cameras installed on conveyor belts, can identify unwanted materials real time and analyse particle size distribution. When the system detects an out-of-specification fraction or contaminant, it activates a mechanical gate or air ejection system to separate it. This technology, already well established in construction and demolition waste (CDW) plants, significantly improves the purity of recovered fractions and reduces the need for manual sorting, which is often risky and inefficient.

Process analysis and optimization: Beyond classification, AI algorithms can process historical system data to detect patterns or inefficiencies that would go unnoticed by the human eye. This analytical capability allows processes to be adjusted in real time, reducing energy intensity (kWh/t) and maintaining more stable byproduct quality. To begin applying these models, a few weeks of records and a basic set of labelled images are usually sufficient, provided that operating conditions are constant.

### 2.3.4. Data analytics and decision support

Beyond artificial intelligence and automation, data analysis, from descriptive statistics to interactive dashboards, is essential for converting telemetry into concrete and useful decisions.

Support for operational decision-making: Analysing historical and real-time data on waste generation allows plant managers to move from reactive to predictive management. Practical applications include optimizing work shifts, properly sizing intermediate storage areas, and identifying the exact economic break-even point for sending a batch to recycle, based on the accumulated volume and its quality characteristics.

Strategic performance monitoring: At the strategic level, analytical tools allow Key Performance Indicators (KPIs) to be calculated by production line, shift, or product family. Some of the most relevant include:

- Material efficiency: tons of waste per ton of product.
- Energy intensity: energy consumption per unit produced (kWh/t).
- Circularity: percentage of waste diverted from landfill.

These indicators provide an objective basis for driving continuous improvement and complying with the reporting frameworks established by the European circular economy (Voukkali et al., 2023; EEA, 2024).

Stakeholder engagement: Data analysis is also a powerful tool for driving behavioural change. Showing operators—or even local communities—visual data on waste reduction encourages more responsible material management. In addition, this data serves as a concrete basis for training activities associated with initiatives such as RockChain.

### 2.3.5. Mobile applications and stakeholder engagement

Mobile applications have become a key tool for putting ICT directly into the hands of operational staff and external actors involved in the value chain.

Field operations: In quarries and processing plants, these apps allow workers to perform tasks directly from the field, without having to return to a fixed workstation:

- Incident reporting: They allow immediate recording of spills, blockages, or contamination events, including photos and geolocation data.
- Task verification: They facilitate real-time confirmation of actions such as cleaning, moving, or inspecting containers.
- Digital guides: They integrate checklists for regulatory compliance and microlearning modules on the proper handling of rock by-products.

Linkage with the extended chain: Beyond facilities, mobile applications improve coordination with workshops, transporters, and other partners, replicating models already established in urban waste management:

- Logistical coordination: They allow real-time sharing of collection schedules and acceptance criteria with small workshops or transport contractors.
- Environmental monitoring: They offer the possibility of reporting illegal dumping sites, thus creating a two-way communication channel that helps synchronize actions between producers, transporters, and recyclers.

### 2.3.6. Blockchain and integrated architectures

Blockchain technology, as a form of Distributed Ledger Technology (DLT), responds to a key need in waste management: having a transparent and tamper-proof history throughout the entire value chain.

Immutable digital record: Each batch of sludge or rubble is digitally represented as a sequential asset. At each stage (generation, conditioning, loading or reception) an event is recorded with a timestamp and cryptographic signature from the responsible actor. Once validated and incorporated into the record, that data cannot be modified. This unalterable history reinforces trust between business partners and authorities, especially in cross-border shipments where traceability and legal responsibility are critical (Lim et al., 2021; Bułkowska et al., 2024).

IoT and smart contracts: Pilot studies have demonstrated the potential of combining blockchain with IoT sensors through so-called ‘smart waste contracts. In these cases, the code in the blockchain itself executes automatic actions based on the data captured by sensors. For example, if a batch arrives at the correct destination and sensors confirm that the moisture content is below the agreed limit, the system can automatically release a payment or issue a certificate of acceptance. This reduces the administrative burden and avoids payment delays (Lamichhane, 2017).

Hybrid architecture (on-chain and off-chain): It is important to note that blockchain does not operate in isolation, but rather as part of a broader architecture. For it to be viable, a hybrid approach is required:

- On-chain: Only essential metadata (such as hashes, timestamps, or transaction summaries) is stored to ensure the integrity of the system.

- Off-chain: Heavier files (such as complete reports, detailed certificates, or images) are stored in traditional databases or decentralised storage solutions such as IPFS.

Both levels must be connected to existing enterprise resource planning (ERP) or manufacturing execution system (MES) systems, avoiding data duplication. This pragmatic design combines the security of blockchain with the efficiency of traditional ICT tools (Berg et al., 2020; Lim et al., 2021).

## 2.4. EU policy framework

European policy on waste and resource efficiency is being structured around a key principle: in sectors with high material use, circularity is not possible without data. Understanding what happens to materials at each stage of the process increasingly requires the use of digital tools.

This framework is based on three pillars that define both the regulations and the financing opportunities for the natural stone sector.

### 2.4.1. European Green Deal.

This is the EU's roadmap for achieving climate neutrality by 2050. Beyond decarbonisation, it proposes a ‘just transition’ for resource-intensive sectors such as construction and extraction.

Implications for the stone sector: The industry must move away from the linear ‘extract-use-dispose’ model and move towards closed cycles where sludge and debris are reincorporated into the production process or related markets.


*Figure 5: European green deal.*

Data requirement: It is not enough to declare progress; it must be demonstrated. Companies must quantify waste generation, recovery rates and environmental benefits with verifiable evidence (European Commission, 2019).

### 2.4.2. Circular Economy Action Plan (CEAP, 2020).

This plan implements the objectives of the Green Deal through specific product regulations. It promotes waste prevention, high-quality recycling and the elimination of hazardous substances to facilitate safe reuse.

Key instrument: Introduces eco-design regulation for sustainable products (ESPR) and the Digital Product Passport (DPP).

Relevance to the sector: For stone by-products to be accepted into construction supply chains, they must have a 'digital identity' certifying their origin, composition and safety, thereby generating confidence among buyers (European Commission, 2020)..

### 2.4.3. Digital Europe Programme (DIGITAL).

While the Green Deal sets the objectives, the DIGITAL programme provides the means. Between 2021 and 2027, it finances the technological capabilities needed to put the policy into practice.

Priority areas: Artificial intelligence, cloud/edge computing and data spaces.

Application: It reduces barriers to implementing IoT networks and traceability platforms by financing the infrastructure needed to achieve circularity objectives (European Commission, 2023).

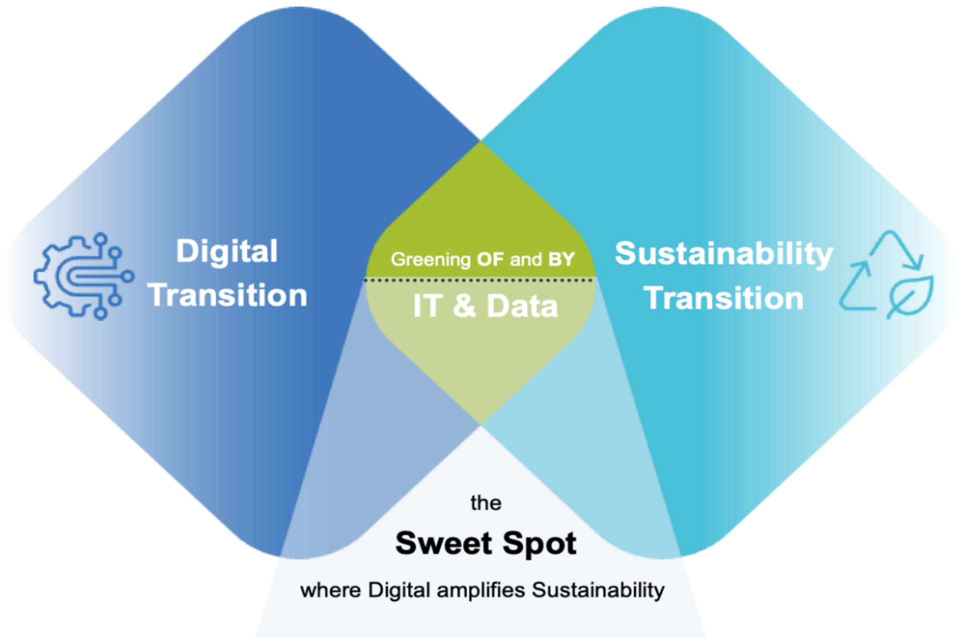


*Figure 6: Twin transition.*

#### 2.4.4. Implications for RockChain

The combination of these policies creates a favourable environment for RockChain. The alignment between the Green Deal (circularity objectives) and the DIGITAL programme (technology financing) reinforces the validity of the project's approach. By integrating IoT, AI, and blockchain to manage stone waste, RockChain not only develops technically sound solutions, but also responds directly to the EU's priority for a data-driven green transition.

# 3. WASTE MANAGEMENT AND IT ADOPTION CURRICULA

To assess the sector's level of preparedness for digital circularity, this chapter presents a comparative analysis of four key countries within the project: Spain, Germany, Croatia and Romania.

The study is structured around three fundamental questions that provide a clear picture of the current situation:

- Operational reality: How is waste currently managed in the natural stone sector?
- Digital maturity: How integrated are digital technologies in daily operations?
- Drivers of change: What projects, programmes and policies are accelerating this transformation?

The objective goes beyond a simple diagnosis. The aim is to identify viable entry points for implementing traceability systems throughout the value chain, from extraction to waste recovery.

This approach is particularly relevant at the European level. Construction and mining/quarrying together account for the largest volume of waste generation in the EU. Therefore, sludge and debris from stone constitute a strategic flow of materials that must be monitored, recovered and transformed into secondary raw materials to meet the objectives of the circular economy (Eurostat, 2024).

This section will detail how these technical trends and regulatory frameworks translate into concrete opportunities and specific training needs for each country analysed.

## 3.1. GERMANY

Germany represents a paradox within the European landscape: it handles enormous volumes of mineral waste (more than 200 million tonnes per year) with recovery rates exceeding 90% but still relies heavily on low-tech downcycling processes (such as landfilling). The challenge is no longer waste collection but rather using digital tools to transform it into high-quality secondary materials.

The sector is beginning to move away from simple logistical solutions towards advanced technological solutions, with the aim of transforming ‘rubble’ into data-rich assets that are compatible with advanced manufacturing and construction standards (BMUV, 2023; Kreislaufwirtschaft Bau, 2024).

### 3.1.1. IT adoption and digitalisation initiatives

Unlike other markets where digitisation begins with administrative tasks, waste management in Germany is rapidly advancing towards operational automation and AI-based sorting.

- From logistics to process control: While the use of GPS and telemetry is common in C&D logistics, the next step is in automated sorting plants. The most advanced facilities are integrating near-infrared (NIR) sensors and hyperspectral spectroscopy with robotic arms to separate mineral fractions not only by size, but also by chemical composition.
- The data gap: Despite the maturity of this hardware, there is a large gap in data interoperability. Information often remains ‘locked’ within proprietary software. The current effort is to break down these silos using cloud-based platforms that can aggregate data from crushing plants, excavators, and trucks, calculating real-time indicators such as $CO_2$ emissions per tonne or material purity (Borchard et al., 2022; Onur, 2024).

### 3.1.2. Relevant projects, programmes and policies

Germany is home to several high-level research and innovation projects that specifically address the intersection of technology, heavy industry and circularity. These initiatives go far beyond simply supporting SMEs, focusing instead on defining the technical standards of the future for the sector.

- BLOCKWASTE (Blockchain for Waste Management): This project directly addresses the ‘trust gap’ in waste data. With the participation of the Fachhochschule Bielefeld (Bielefeld University of Applied Sciences), BLOCKWASTE explores how blockchain technology can generate tamper-proof records for waste streams. It goes beyond theory, developing educational tools and case studies on how to use distributed ledgers to certify that a specific batch of waste has been treated according to regulations, a crucial capability for high-value stone by-products (BlockWASTE Consortium, 2023).


*Figure 7: Blockwaste project.*

- SmartRecycling-Up (AI and robotics): Led by DFKI (German Research Centre for Artificial Intelligence), this project is a prime example of how to transfer advanced technology to the waste sector. It develops AI-based control systems for heavy machinery (cranes and excavators) to automatically sort bulky and construction waste. The system uses advanced computer vision to “see” and separate valuable fractions from mixed piles, demonstrating how AI can physically intervene in the material cycle, reducing reliance on dangerous manual sorting (DFKI, 2025).

- DigiEcoQuarry (German pilot - Mammendorf): The Mammendorf quarry, operated by CSI near Magdeburg, is a key pilot site for this Horizon 2020 project. It validates the 'Innovative Quarry System' (IQS) in a real hard rock environment. The pilot integrates sensors, drones and data platforms to optimise the extraction and processing chain. For the stone sector, this demonstrates live how 'waste' (fines and tailings) can be reduced at source through data-driven blasting and processing decisions (DigiEcoQuarry Consortium, 2024).

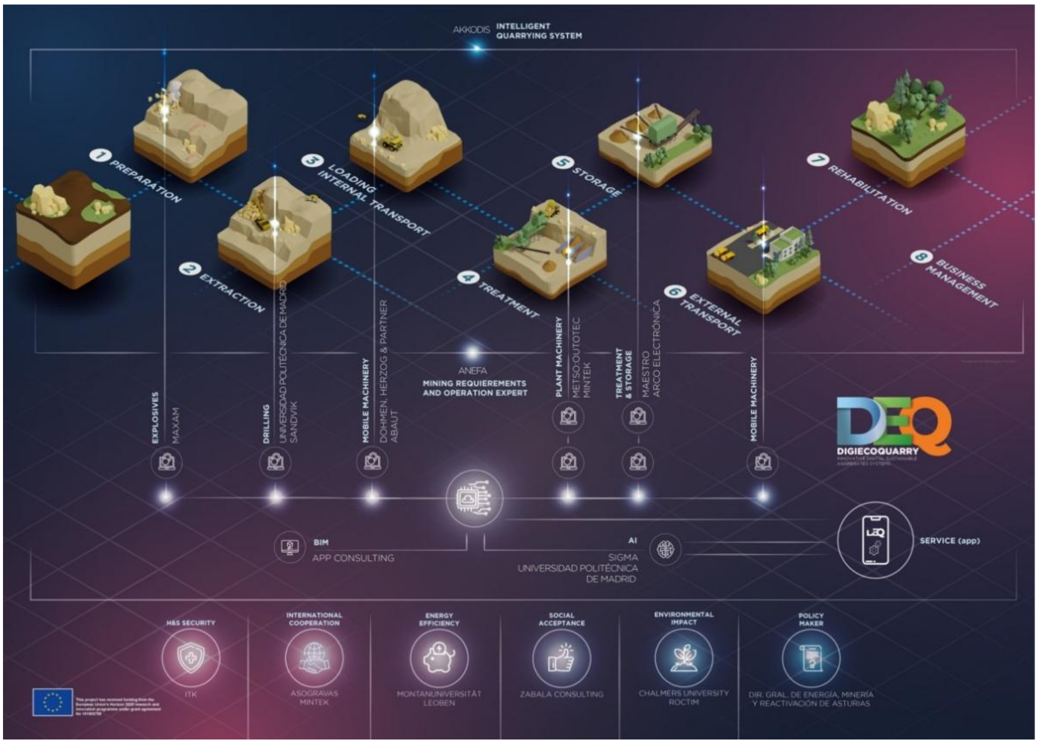


*Figure 8: DigiEcoQuarry project.*

- KaSyTwin (Digital Twins for Infrastructure): Funded by the German Ministry of Digitalisation and Transport (BMDV), this project builds digital twins of sewer systems using AI and robotics. Although it focuses on water infrastructure, it illustrates a crucial trend for stone materials: the move towards 'predictive maintenance' and the life cycle management of mineral assets. It shows how stone-based infrastructure can be managed as a digital entity, providing data that extends the useful life of the asset and optimises its recovery at the end of its life cycle (BMDV, 2024).

### 3.1.3. Implications for RockChain

Germany represents a sophisticated but demanding environment for the implementation of RockChain pilots. Although the country has high operational standards, it also imposes strict barriers to the incorporation of new recycled materials.

- A testing ground for high-quality recovery: Unlike other markets focused on basic reuse, Germany offers the possibility of developing training programmes focused on quality-oriented recycling. RockChain's training activities can focus on how to use digital tools, such as IoT and blockchain, to demonstrate that stone by-products meet the demanding chemical and physical requirements set by the Building Substitutes Ordinance (EBV).
- Data interoperability as a key competence: With initiatives such as DigiEcoQuarry and SmartRecycling-Up active in the country, there is a clear need for professionals capable of connecting the world of heavy industry with data analysis. Therefore, the training plan should emphasise the use of digital twins and the integration of sensor data into existing ERP systems, thus moving beyond the traditional approach of manual reporting.
- Strategic alliances: The strong presence of leading research centres, such as DFKI, and digitisation initiatives for SMEs, such as Mittelstand-Digital, provides a natural network for disseminating RockChain's results. In this context, future technicians would not only be trained in waste management, but also in a broader vision of 'industrial resource management', in line with the national strategy that seeks to position waste as standardised products for the market.

## 3.2. SPAIN

In many ways, Spain has become a 'living laboratory' for applying circularity principles in the minerals sector. Driven by the 'España Circular 2030' strategy and the strict requirements of Law 7/2022 on waste and contaminated soil, the industry is moving away from simple waste disposal towards recovery using advanced technologies.

The focus is no longer just on reducing waste, but on building a digital ecosystem where quarries, processing plants and recycling centres are interconnected. This change is supported by an active network of technology centres (such as Tecnalia, IETcc-CSIC, CTM) and industry associations such as ANEFA.

### 3.2.1. IT adoption and digitalisation initiatives

Spain leads some of Europe's most advanced projects based on the concept of the 'Digital Quarry'. Digitisation is no longer just an aspiration: it is being tested and applied in real operating environments.

- Sensorised production: Through projects such as DigiEcoQuarry, innovative mining systems (IQS) are being implemented in Spanish quarries. These systems use IoT sensor networks to capture real-time data on extraction and processing, allowing the product-waste ratio to be optimised at source.

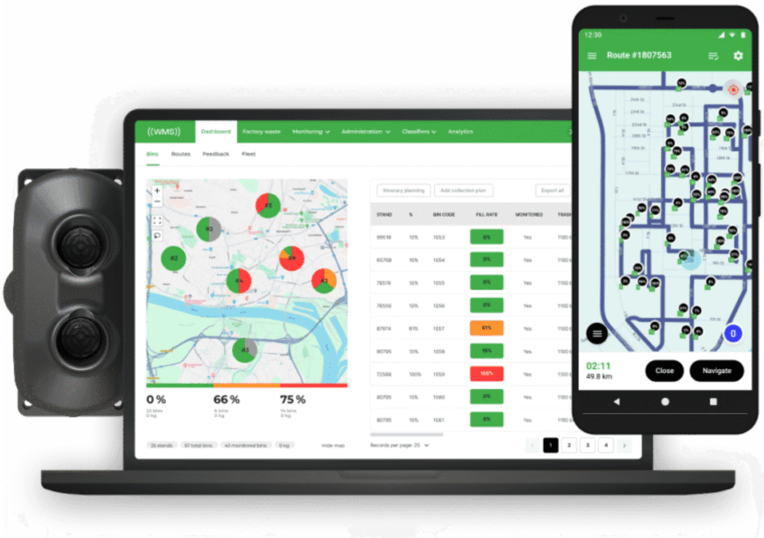


*Figure 9: Sensoneo.*

- Massive IoT deployment: Beyond quarries, Spain stands out for its digital maturity in waste logistics. Madrid, for example, is deploying Europe's largest smart waste project, with more than 11,000 sensors (Sensoneo) installed to optimise collection routes in real time. This scale demonstrates that the IoT infrastructure needed to track industrial stone waste is already viable and operational in the country.
- Volumetric control with drones: The use of UAVs to manage stockpiles is becoming common practice in large granite and marble quarries. Beyond aerial photography, photogrammetry is used to calculate exact volumes of waste and by-products, integrating this data into ERP systems for accurate inventory valuation (Himmy et al., 2025).

### 3.2.2. Relevant projects, programmes and policies

Spain has a very active ecosystem that connects digital technologies with mineral waste management. Spanish entities also play a prominent role in international initiatives, reinforcing knowledge exchange at the European level.

- BLOCKWASTE (Education and Blockchain): Although the project stands out for its focus on blockchain, its application in the stone sector is led by the CTM (Marble, Stone and Materials Technology Centre). CTM adapts blockchain training for stone waste managers, ensuring that SMEs in the sector understand and can apply this technology at a practical level.

- ICEBERG (Circular Construction): This flagship H2020 project focuses on the recovery of high-value materials from construction and demolition waste (CDW). With a strong Spanish component led by Tecnalia and Ihobe, ICEBERG validates technologies such as hyperspectral imaging for the automated classification of concrete and stone fractions, connecting the end of life of buildings with new secondary market materials (ICEBERG Consortium, 2025).

*Figure 10: Iceberg European project.*

- DigiEcoQuarry and VALREC: As detailed in the sector overview, these projects are fundamental to national innovation. ANEFA leads DigiEcoQuarry, which focuses on the digitisation of the extraction phase, while Sacyr leads VALREC, which focuses on tracing recycled aggregates back to the construction process. Together, they cover the entire cycle, from origin to return to market.
- PERTE Circular Economy: The 'Strategic Project for Economic Recovery and Transformation' (PERTE) acts as the main financial driver. It includes specific lines of support for companies to implement digital traceability systems and modernise waste treatment facilities, directly supporting the adoption of the mentioned technologies (MITECO, 2024).

### 3.2.3. Implications for RockChain

Spain offers an ideal environment for implementing RockChain project pilots, with key features such as:

- Access to real pilots: Initiatives such as DigiEcoQuarry, VALREC and ICEBERG offer specific case studies that can be integrated into training activities.
- Technological maturity: The presence of technologies such as robotic sorting and digital twins provides advanced content for training plans.
- Solid institutional support: The accreditation capacity of IGME-CSIC laboratories allows digital skills to be linked to physical material testing standards.

## 3.3. ROMANIA

Romania represents a unique opportunity for a 'technological leap' within the European context. Although it has historically had some of the lowest recycling rates in the EU — with landfill still the predominant practice — the country is undergoing rapid modernisation of its waste management infrastructure, driven by the National Recovery and Resilience Plan (PNRR).

Far from replicating traditional models, the country is betting directly on digital solutions. With significant investment in 'eco-islands' and smart monitoring systems, Romania is turning its waste management gap into a testing ground for the mass deployment of IoT (European Commission, 2023; Government of Romania, 2022).

### 3.3.1. IT adoption and digitalisation initiatives

Unlike more established markets, where legacy systems can slow down innovation, Romania is building a completely new infrastructure, designed from the outset to be 'smart'.

- National IoT deployment (Eco-Islands Project): Under the PNRR, thousands of 'digitised eco-islands' are being installed in cities such as Timișoara, Constanța and Iași. These smart collection points are equipped with GSM modules, fill sensors and access control systems. This is a nationwide deployment of the same IoT technology needed to track stone waste containers, confirming the technical feasibility of this network (Ministry of Environment, 2024).
- Digital twins in construction: Cluj-Napoca, a pilot city for the NetZeroCities mission, is leading the way in using digital twins to model urban emissions and material flows. This initiative combines satellite data (Copernicus) with local sensors to track the environmental footprint of the built environment. It is a model that can be easily scaled up to track the life cycle of construction materials and quarry products (NetZeroCities, 2024).

### 3.3.2. Relevant projects, programmes and policies

Various strategic initiatives are laying the groundwork for moving towards a digital circular economy in the Romanian stone sector:

- ROCES 2030 (National Circular Economy Strategy): This strategy clearly identifies the construction and mining sectors as priority areas. It calls for the creation of a national digital platform for waste data, replacing paper reports. For stone companies, this anticipates an upcoming regulatory obligation: to digitise their inventories if they want to participate in the secondary raw materials market (Romanian Government, 2023).
- Geocycle Romania (Industrial co-processing): Part of the Holcim group, Geocycle operates advanced pre-treatment facilities that convert industrial mineral waste into alternative resources for cement kilns. Its plants in Aleșd and Câmpulung apply laboratory characterisation and strict traceability. This existing industrial infrastructure represents a concrete pathway for the recovery of stone sludge, provided that the required digital quality standards are met (Geocycle, 2024).


*Figure 11: Geocycle project.*

- Green Energy Innovative Biomass Cluster: Located in the Centru region, this cluster manages circular economy projects such as BioRural and SPIRE, connecting biomass and rural waste streams with industrial users. Its ‘local value chains’ model is directly applicable in quarry areas, where stone waste could be treated locally, avoiding costly and unnecessary transport (Green Energy Cluster, 2024).

### Implications for RockChain

Romania offers a high-impact environment for implementing the RockChain curriculum, characterised by strong demand for digital skills to accompany the new infrastructure.

- From paper to the cloud: The most immediate training need is to support SMEs in the transition from manual records to the digital standards required by the new national platform. RockChain can offer the practical guidance needed to facilitate this inevitable change.
- Leveraging the new infrastructure: With the expansion of smart eco-islands, a unique opportunity arises to train technicians capable of operating and maintaining IoT assets applied to waste management. These skills are applicable in both urban and industrial contexts, such as the management of quarry slurry tanks.
- Regional training centres: Clusters such as Green Energy or the innovative ecosystem in Cluj offer networks ready for the dissemination of the training programme, ensuring that digital skills reach the professionals who will operate the country's new waste management system.

## 3.4. CROATIA

Croatia is undergoing a critical phase of transformation in waste management, accelerated by the urgent need for reconstruction following recent earthquakes. Although the total volume of waste is moderate compared to large EU countries, mineral and construction waste streams account for the majority of the national profile.

The sector is transitioning from a heavy reliance on landfills to a strategic approach focused on recovery. The National Waste Management Plan 2023–2028 prioritises the modernisation of infrastructure and the implementation of digital tracking systems, with the aim of converting large volumes of demolition rubble into useful resources rather than environmental liabilities (Official Gazette, 2023).

### 3.4.1. IT adoption and digitalisation initiatives

Digitisation in Croatia's stone and construction sector is establishing itself as a key tool for improving the traceability and control of large volumes of materials.

- Digital records of rubble: Following the recommendations of the World Bank, the country is developing digital recording systems for construction and demolition waste (CDW). These will replace paper records with mandatory digital reports on demolition sites, establishing a layer of traceability that is easily applicable to quarry waste (World Bank, 2023).
- Smart Specialisation Strategy (S3): The national S3 strategy (2021–2027) includes 'Sustainable Environment' as a priority and promotes technologies such as BIM (Building Information Modelling) and modular construction. This approach allows materials — including stone — to be digitally tagged from the design phase, facilitating their recovery in later stages.
- Pilots in waste logistics: As part of cross-border projects, several municipalities are testing recycling yards equipped with IoT sensors. These pilots allow real-time monitoring of waste inflows and outflows, providing a first proof of concept for digital materials management in the region.

### 3.4.2. Relevant projects, programmes and policies

The Croatian ecosystem is marked by active international collaboration and the development of strategic projects with a strong technological component:

- Action Plan for the Circular Economy in CDW: Developed in conjunction with the World Bank, this plan lays the foundations for the future of the sector. It explicitly proposes the digitisation of waste data to prevent illegal dumping and promote the secondary aggregates market. For companies in the stone sector, this roadmap makes it clear that digital compliance will soon be a market requirement (World Bank, 2022/2023).

- CircleAware (Interreg Project): Connecting Croatia with Bosnia and Montenegro, this project tests innovative waste separation solutions. In the town of Trilj, a digital solution is being implemented to monitor waste quantities at recycling yards. Although focused on municipal and small-scale waste, the model, which integrates physical separation with digital tracking, is easily replicable for industrial stone waste (Interreg IPA, 2024).


*Figure 12: Interreg Croatia-Bosnia-Montenegro*

- CrossWaste (Interreg Project): Led by EKO-DUNAV d.o.o., this project focuses specifically on infrastructure for construction waste, the most abundant waste stream in the region. Unlike other more theoretical approaches, CrossWaste develops concrete pilots where waste is used as sustainable material in local road works, demonstrating how to transform rubble into useful infrastructure and combat illegal dumping through recovery (Interreg IPA, 2024).
- KOdeCO net zero (Holcim Croatia): This is the first major industrial project in Croatia co-financed by the EU Innovation Fund. Although its main objective is carbon capture in cement production, it integrates principles of circularity and large-scale digital management. It sets a new ‘Industry 4.0’ standard for mineral processing in the region (European Commission/Holcim, 2024).


*Figure 13: KOdeCO project.*

## Implications for RockChain

Croatia offers an active environment with high demand for RockChain training solutions, in a context driven by reconstruction and digitalisation:

- Reconstruction as an opportunity: Strong demand for materials derived from reconstruction provides an ideal platform for training professionals in how to transform stone waste into certified products for public works.
- Digital compliance training: With the launch of digital construction waste registers, there is a clear need for practical training. RockChain can fill this gap by offering content on the efficient use of digital reporting tools.
- Expanded regional reach: Thanks to projects such as CircleAware and CrossWaste, content developed for Croatia can be easily extended to neighbouring countries outside the EU, such as Bosnia and Montenegro, multiplying RockChain's impact in the Balkans.

# 4. RESULTS ANALISYS

The purpose of this chapter is to assess the degree of alignment between the current educational offering in the four partner countries of the project (Spain, Romania, Croatia and Germany) and the new emerging technological demands of the natural stone sector.

This is a strategic gap analysis, comparing two different sets of data collected throughout the project:

- Demand (what the industry wants): Based on the findings in Chapter 3, the 'operational reality' of modern quarries and processing plants is defined. There is a clear transition towards data-driven management, which requires specific skills in IoT sensorisation (for sludge and fines), automatic classification with AI, volumetric monitoring using drones (UAVs) and traceability systems (blockchain or Digital Product Passport - DPP).
- The offer (what the education system offers): Based on the mapping carried out in WP2, current programmes in higher education and vocational education and training (VET) are analysed, with a special focus on the areas of Environmental Engineering, Waste Management, Information Technology and Blockchain.

The main focus is to assess the level of operational readiness. In other words: if a company in the sector decides to digitise its waste flows today, are there professionals in the local labour market with the hybrid skills needed to support this change?

The analysis attempts to answer whether current training profiles are still generalist (e.g. purely ICT developers or geologists without digital skills), or whether there are already interdisciplinary pathways that connect digital tools with industrial materials management.

In the four countries analysed, a common structural pattern can be observed:

- Technological expansion: The range of courses related to blockchain, data analysis and Industry 4.0 is growing rapidly.
- Sectoral strength: Traditional programmes in mining, environmental sciences and waste management remain strong and well established.
- Integration gap: There remains a significant disconnect between the two areas. Few curricula manage to bridge these two dimensions, for example by using industrial mineral waste as a case study to teach digital technologies.

The following sections provide a detailed analysis by country, highlighting specific strengths, identifying critical skills gaps and proposing concrete opportunities for innovation in training curricula.

## 4.1. GERMANY

Germany has established itself as a mature benchmark within the European landscape, with exceptionally high recovery rates (over 90% for mineral construction waste) and a rigorous regulatory framework based on the Substitute Building Materials Ordinance (EBV). However, the sector faces a paradox: although the physical recycling infrastructure is highly developed, the digitisation of the 'last mile', i.e. the connection between operational waste flows and real-time data, remains uneven.

### Strengths in IT adoption and training offer

Germany combines a strong data culture with high-tech industrial capacity, providing a solid foundation for advancing towards a digital circular economy.

- Established data culture: Unlike other markets with limited information, Germany has had detailed reports on mineral material flows since the mid-1990s thanks to the Kreislaufwirtschaft Bau initiative. This empirical basis—statistics, mass balances, flow maps—can be used directly in simulations and applied digital training.
- Tradition of technical training and dual vocational training: The German dual system and its technical universities offer first-class training in process engineering and automation. The approach is deeply technical, ensuring that graduates understand both industrial processes and how machinery works.
- High-level operational projects: The presence of advanced initiatives demonstrates that the technology is already in operation, and not just in the experimental phase.
    - SmartRecycling-Up: AI-based robotic sorting projects provide real-world cases for teaching cognitive automation applied to waste.
    - DigiEcoQuarry: The pilot site in Mammendorf represents a fully sensorised environment, ideal as a 'digital classroom' for teaching IoT applications in extractive processes.

### Weaknesses and gaps

The main obstacle in Germany is not a lack of technology, but rather the disconnect between large-scale strategies and their implementation in everyday practice.

- Implementation gap: A survey of 130 companies in the sector shows that, although digitalisation is seen as a strategic priority, its practical application tends to remain at the administrative level (such as invoicing or customer portals), without reaching operational processes, such as real-time sludge monitoring or predictive maintenance.
- Curricular silos: A rigid separation between disciplines persists. Blockchain courses tend to be geared towards the financial or logistics sectors, while environmental engineering focuses on physical-chemical properties. There is a

lack of interdisciplinary modules that apply technologies such as DLT or AI to the certification of mineral waste, creating a gap in key competencies for future Digital Product Passports.

- Barriers for SMEs: Although institutes such as Fraunhofer and DFKI are leading the way in technological development, many small quarries and recycling plants lack the technical expertise to translate these innovations into profitable and applicable solutions.

#### Potential for integration with circular-economy principles

Germany offers the ideal context to test training programmes with a “quality-first” approach, moving beyond simple waste diversion to focus on the certification of high-value products.

- Regulatory compliance as a professional skill: With the EBV setting high quality standards for secondary materials, RockChain can deliver specialised training on how to use digital tools to demonstrate compliance. For example, teaching how to use blockchain not for cryptocurrencies, but to create an immutable audit trail that certifies a batch of recycled aggregates meets legal requirements.
- Leveraging real cases: Training programmes can be built directly around data and scenarios from projects like *SmartRecycling-Up* or *DigiEcoQuarry*. Instead of relying solely on theory, students can work with real sensor data from a sorting robot or a quarry crusher to analyse and optimise material recovery.
- Hybrid professional profiles: The National Circular Economy Strategy explicitly highlights the need for “digital enablers”. This provides an institutional foundation for training technicians who can handle both the geotechnical aspects of stone by-products and the data architectures required for future Digital Product Passports.

## 4.2. SPAIN

Spain operates as a “living laboratory” for the stone sector. With a regulatory framework that strictly penalizes landfilling (Law 7/2022) and incentivizes circularity (PERTE Circular Economy), the pressure to modernize is high. The country hosts some of Europe’s most advanced pilot projects, but the skills market has not yet fully caught up with this technological momentum.

### 4.2.1. Strengths in IT adoption and training offer

Spain has the “raw materials” needed for a digital transition, both in terms of industrial pilots and a solid educational base.

Advanced Industrial Pilots: The sector is not starting from scratch. Initiatives like *DigiEcoQuarry* (coordinated by ANEFA) and *VALREC* (led by Sacyr) are already validating complex digital architectures in real operational environments. Spanish quarries are testing Cyber-Physical Systems (CPS) and real-time data platforms for aggregates. Furthermore, the deployment of large-scale IoT systems in urban logistics (e.g., Sensoneo in Madrid) demonstrates the country's readiness to support extensive sensor networks.

Established Educational Verticals: Spain's higher education system provides strong—though often siloed—training tracks:

- Engineering & Environment: Strong degree programmes in Geology, Mining, and Environmental Sciences that cover circular economy regulations and waste valorization.
- Industry 4.0: An expanding catalogue of university and VET programmes focused on IoT, Big Data, and industrial automation.
- Blockchain & IT: A growing offer in distributed ledger technologies, often driven by dynamic tech hubs.

### 4.2.2. Weaknesses and Gaps

The main weakness in Spain is fragmentation. While the individual skills exist, they are rarely integrated in a way that's immediately useful for the stone industry upon graduation.

- The "Generalist" Trap: Waste management curricula typically focus on municipal waste or general industrial effluents, without addressing the specific handling and rheological needs of stone sludge (e.g., moisture control, filter press operation).
- Context-Free Digital Training: Conversely, blockchain and IoT courses are often oriented towards fintech, logistics, or generic manufacturing. Students may learn how to code smart contracts for cryptocurrency, but not how to certify a batch of recycled aggregates. There's a lack of applied digital skills for heavy industry.
- SME Skills Gap: While major tech centers (e.g., Tecnalia, IETcc-CSIC) hold world-class expertise, that knowledge isn't trickling down fast enough to SMEs. Small quarries lack personnel able to translate "Digital Quarry" concepts into daily operations, creating a bottleneck for tech adoption.

### 4.2.3. Potential for Integration with Circular Economy Principles

Spain is uniquely positioned to bridge these gaps by leveraging its strong institutional and project-based ecosystem.

Leveraging Accredited Science: The Natural Stone Laboratory at IGME-CSIC provides standardized frameworks for petrographic and mechanical testing. RockChain curricula can directly integrate these protocols, teaching students how to "digitize" a lab report into a blockchain entry or a Digital Product Passport.

Project-Based Learning (PBL): The existence of active pilot sites like *DigiEcoQuarry* and *ICEBERG* offers a golden opportunity. Curricula can be designed around real datasets—like sensor readings from a crushing plant or hyperspectral images from a sorting robot—so that students train on real-world industrial challenges rather than theoretical models.

Modular Micro-Credentials: Given the urgency outlined in the PERTE Circular Economy initiative, there is a clear market for short, targeted courses. A module titled "Digital Traceability for Mineral By-products" would have immediate value for professionals needing to comply with new waste traceability regulations and taxes.

## 4.3. ROMANIA

Romania represents a "leapfrog" scenario. Historically reliant on landfilling, the country is now bypassing intermediate steps and investing directly in advanced digital infrastructure (eco-islands), driven by its National Recovery and Resilience Plan (PNRR). The challenge is not hardware, it's the shortage of the "human software" required to operate it.

### 4.3.1. Strengths in IT adoption and training offer

Romania's key driver is massive public investment in digital waste infrastructure, generating immediate demand for new skills.

- Investment Boom (Hardware-Led): The nationwide rollout of digitized eco-islands and smart collection systems is creating large-scale demand for technical skills to operate and maintain these systems. Technology is being deployed faster than the workforce is being trained.
- Strategic Direction: The ROCES 2030 strategy and Cluj-Napoca's Digital Twin pilot reflect strong political commitment to data-driven circularity. The national policy explicitly calls for a digital waste data platform.
- Industrial Offtake: The presence of players like Geocycle offers a high-tech industrial partner capable of co-processing waste. Their advanced pre-treatment facilities provide a concrete market for stone by-products—if quality digital data is provided.

### 4.3.2. Weaknesses and Gaps

The main challenge in Romania is the implementation gap, a disconnect between newly acquired infrastructure and current on-the-ground operations.

- Paper-to-Cloud Gap: Many SMEs still rely on manual logbooks. Transitioning to the cloud-based platforms required by the ROCES strategy involves a massive upskilling effort that current curricula are not yet addressing.
- Curricular Focus: University programmes in waste management often focus on municipal waste streams or general pollution control. They rarely address the specifics of mineral industrial waste or the potential of digital tracking for secondary raw materials.
- Technician Shortage: There is a lack of technicians trained to manage the interface between physical waste and digital systems. Graduates may know how to design a landfill but not how to calibrate a smart sensor or manage a digital waste registry.

### 4.3.3. Potential for Integration with Circular Economy Principles

RockChain can act as the “software” layer enabling the new hardware by offering the training content needed to make PNRR investments viable.

- Operational Training: Develop curricula specifically focused on operating and maintaining the new IoT assets (eco-islands, sensors) being deployed nationwide. The skills needed to manage a smart municipal bin are nearly identical to those required for smart quarry waste containers.
- Digital Reporting Compliance: Training should support SMEs in shifting from paper logs to the new national digital reporting systems. This compliance skillset offers immediate employment value.
- Cluster-Based Learning: Use networks like the Green Energy Innovative Biomass Cluster to distribute digital circularity training to regional operators. This model links rural quarries with local industrial valorization routes, creating closed-loop systems that reduce transport emissions and costs.

## 4.4. CROATIA

Croatia is navigating a unique transition driven by post-earthquake reconstruction. This massive engineering challenge has turned construction and mineral waste into a strategic priority, accelerating the need for digital tracking and recovery. The sector is moving from a reliance on landfilling to a scenario where recycled aggregates are urgently needed for rebuilding efforts.

### 4.4.1. Strengths in IT adoption and training offer

The primary strength in Croatia is the convergence of market demand and high-profile industrial investment.

- Reconstruction as a Driver: The booming demand for construction materials creates a subsidized, guaranteed market for high-quality recycled aggregates. This is supported by the World Bank's Circular Economy Action Plan, which provides a roadmap for modernizing the sector.
- Strategic Industrial Projects: Croatia is hosting cutting-edge Industry 4.0 projects. Holcim's KOdeCO net zero (Carbon Capture and Storage) represents a massive investment in decarbonizing mineral processing, proving that the local industry is ready for high-tech solutions. Additionally, the CrossWaste project is piloting the use of recycled construction waste in road infrastructure, demonstrating practical, scalable applications.
- Policy Alignment: The National Waste Management Plan (2023–2028) and Smart Specialisation Strategy (S3) explicitly promote the use of digital registers and modular construction, creating a favorable regulatory environment for digital skills.

### 4.4.2. Weaknesses and gaps

Despite the high-level projects, there is a significant compliance gap at the operational level.

- Digital Compliance Gap: As national digital registries for C&D waste become mandatory to prevent illegal dumping, there is a critical lack of professionals trained to use these systems efficiently. Small operators struggle to move from paper tracking to the new digital reporting standards.
- Siloed Education: While the ICT sector in Croatia is dynamic, it is often disconnected from heavy industry. Engineers may understand the *material* properties of stone (civil engineering), but they often lack the *data* skills to implement traceability or manage digital inventories.
- Uneven Implementation: While flagship projects exist, the average quarry or demolition company still operates with traditional methods. The skills required to "bridge" the gap between a high-tech cement plant and a small recycling yard are missing from current VET programmes.

### 4.4.3. Potential for integration with circular-economy principles

Croatia offers a dynamic environment for Reconstruction-Led Training, where RockChain can serve as a capacity-building tool.

- Compliance & Traceability Training: RockChain curricula should focus on the practical use of the new digital C&D waste registries. Teaching students how to document stone waste to turn it into certified reconstruction material creates immediate employability.

- Cross-Border Scaling: Through projects like CircleAware and CrossWaste, training modules developed in Croatia can be easily scaled to neighboring non-EU countries (Bosnia and Herzegovina, Montenegro). This positions Croatia as a regional hub for digital circularity skills in the Balkans.
- High-Tech Case Studies: The KOdeCO project offers a world-class case study for teaching the principles of industrial decarbonization and digital process control. Integrating this into curricula would expose students to the absolute forefront of European mineral processing technology.

# 5. BEST PRACTICES

This chapter shifts from analysis to implementation, highlighting real-world cases where digital technologies are improving waste management. These examples offer clear lessons for the ornamental stone sector and inform the RockChain curriculum.

We focus on three areas where digital tools have shown proven value: IoT logistics, construction waste valorization, and digital skills training. These technologies show that the “Digital Quarry” is no longer hypothetical, it’s a working model ready for replication.

## 5.1. PROVEN DIGITAL SOLUTIONS

Across Europe, digitalization is moving from pilots to large-scale implementation. We identify three proven solutions relevant to the stone sector:

### IoT & Smart Logistics (Efficiency Layer)

Key Tools: Fill-level sensors, load cells, and route optimization.

- Sensoneo (Madrid): Over 11,000 sensors cut collection distances by ~20%.
- SENS (H2020): Data-driven routing cut $CO_2$ emissions by up to 60%.

Why it matters: This approach applies directly to stone waste. Sensors on sludge tanks or skips help optimize truck routes and avoid overflows, improving safety and cutting costs.

### Digital Tools for CDW (Valorization Layer)

Key Tools: Hyperspectral imaging (HSI), BIM, Digital Product Passports.

- ICEBERG & RECONMATIC: Use AI to sort mineral fractions; BIM to track reuse.
- CityLoops: Links demolition and construction through urban data platforms.

Why it matters: Stone by-products must be treated as valuable construction materials. Tools like DPPs offer the traceability needed to access high-value markets.

### EdTech & Blockchain (Skills Layer)

Key Tools: E-learning platforms, blockchain-based case studies.

- BlockWASTE (Erasmus+): Teaches blockchain through real waste scenarios.
- EduZWaCE & Zero Waste Build: Introduce circular economy into VET training.

Why it matters: Technology is only as useful as the people who apply it. These projects show how digital skills can be taught using hands-on, sector-specific tools.

## 5.2. LESSONS FOR THE STONE SECTOR

From these examples, five key takeaways emerge:

- Start with KPIs, not tech: Don't install sensors until you define what to measure (e.g., €/ton processed, kWh/ton).
- Treat waste as product: Tools like DPPs and lab data are essential for legal and market compliance.
- Interoperability is essential: Systems must share data across companies. Siloed solutions fail.
- Rules over code: In blockchain, governance matters more than technology.
- Bridge the "hybrid" gap: The sector needs professionals who understand both materials and data systems.

## 5.3. ROCKCHAIN'S STRATEGIC ROLE

The digital shift creates a real need for RockChain. Its value lies in making digital tools accessible, understandable, and practical for the stone sector:

### A Risk-Free Testing Ground

Real pilots are expensive and risky. RockChain acts as a safe simulator—companies and students can test IoT, routing, and traceability without disrupting operations or investing capital.

### Bridging the IT–Stone Gap

Digital and quarry teams speak different languages. RockChain integrates real material parameters into digital workflows, helping users navigate both physical and digital environments.

### Preparing for Regulation

Digital Product Passports and waste traceability laws are coming. RockChain helps train professionals to meet these requirements now, making compliance part of everyday operations.

RockChain could be more than a learning tool it could be a strategic enabler, helping the stone industry embrace the digital shift through hands-on, low-risk training grounded in real-world applications.

# 6. CONCLUSIONS

A review of waste management and IT adoption in Spain, Germany, Romania, and Croatia shows a sector at a crossroads. Mineral and construction waste dominate in all four countries, placing the stone industry at the heart of Europe's circular economy. Yet while the digital tools exist (IoT sensors, AI sorting, drones) their use is still limited. High-tech pilot projects run alongside traditional, paper-based systems in most small and medium enterprises.

The problem isn't technology, it's people. There's a clear gap between available innovations and the skills needed to apply them in day-to-day operations. Quarry managers and plant operators often lack the hybrid know-how to connect physical processes (like sludge handling or material testing) with digital platforms.

What works, according to best practices across the EU, is focusing on outcomes. Digital systems succeed when they help optimize KPIs like energy use or material quality—not just when they add gadgets. For the stone sector, this means shifting the mindset: waste should be managed like a product, with quality checks and traceability baked in from the start.

This is where education falls short. Environmental courses teach the rules, but not the tools. As regulations tighten (like Germany's EBV, Spain's Law 7/2022, or the EU's Digital Product Passport) knowing how to report data will be as important as knowing the law. The current training landscape isn't preparing workers for this shift.

There's also a mismatch in training design. IT students rarely learn about industrial materials, and engineering students rarely touch digital systems. Countries like Romania and Croatia are building digital infrastructure fast, but lack the technicians to operate and maintain it. This creates a real risk that high-end systems will sit unused.

The stone sector doesn't need new tech, it needs better ways to connect the tech to real-world problems. That's where RockChain can make a difference: acting as both translator and testing ground. By simulating realistic quarry scenarios with digital tools, it helps reduce risk, build confidence, and train a new kind of professional—one who can turn stone waste into certified, valuable material.

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