RockChain Course:
UNIT 1.
Introduction to the Ornamental Stone and Mining Industry.

"Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them."

Contents

1. OVERVIEW OF THE SECTOR: SCALE, IMPACT, MAIN COUNTRIES

1.1. European Stone Sector — Scale and Main Countries

In Europe, the natural stone market revenue was approximately USD 1,879.8 million (≈USD 1.88 billion) in 2024, with an expected rise to USD 2,695.1 million (≈USD 2.7 billion) by 2030, reflecting a CAGR of 6.4%.

Another source estimates the broader Europe natural stone & marble market at USD 16.04 billion in 2021, growing to USD 18.44 billion in 2025 (CAGR ≈3.55%), and projected to reach USD 24.39 billion by 2033.

1.2. Top European Producers and Exporters

Italy: Leading EU producer (≈51% of extraction and processing). Renowned for high-quality Carrara marble and numerous granite deposits.

Spain: Second in EU (≈19% of output), with strong granite, marble, and slate production—particularly from Galicia**,** responsible for ≈90% of Europe's roofing slate (≈4 million tons/year).

Portugal: Key exporter of granite and limestone, with popular gray and pink granite used extensively in paving and cladding.

Greece: Famous for marble; also a producer of granite in lesser volumes

Norway, Sweden, Finland: Notable for high-strength granites (e.g., Blue Pearl, Balmoral Red) largely exported as raw blocks.

Germany, France, Poland: Own domestic quarries but rely significantly on imports for processed stone goods; renowned traditional production zones such as the Bavarian Forest in Germany and Brittany in France.

Eastern Europe (Ukraine, Kazakhstan, etc.): Have smaller-scale, largely domestic markets but carry geological potential.

1.3. Stone types and segments

In Europe, granite holds the largest revenue share (≈37.7%) in 2024.

Marble is the fastest-growing segment across both Europe and the U.S.

In Spain, slate is a super-dominant material for roofing, accounting for 90% of Europe's slate roof supply.

1.4. Global Natural Stone Sector — Scale & Growth

Market Size

The global natural stone market is value at USD 41.81 billion in 2025 and is projected to reach USD 43.27 billion in 2026, steadily progressing to USD 60.86 billion by 2035, with a CAGR of 3.5% from 2026 to 2035.

The global Natural Stone market grew rapidly in 2022 and is expected to grow further by 2028, with a significant CAGR in the forecast period. With increased demand for aesthetic and durable construction materials and with advancement in cutting, finishing, and installation technologies, the natural stone market has been fuelled. With its uses in construction, interior designing, and landscaping, natural stone has found an immense market with its durability, timelessness, and versatility. Further, there is an increasing trend for using eco-friendly and sustainable building materials, which further supports the demand for natural stone across different industries.

Figure 1. Global Natural Stone Market Size until 2035. Source: https://www.businessresearchinsights.com/market-reports/natural-stone-market-118807

Regional Distribution

- Asia-Pacific dominates, contributing over 46% of global demand, especially driven by China and India, fuelled by rapid urbanization and infrastructure growth.
- Europe holds about 18.5% of the global natural stone market in 2024, and approximately 25% of global consumption
- North America accounts for roughly 21% of consumption.

Key Drivers and Trends

- Construction remains the core driver (≈42% of demand), particularly for flooring, cladding, and high-end architectural applications.
- Renovation/restoration (especially of historic sites) contributes ≈28% of demand.
- Sustainability trends are boosting stone use: about 19% of green building projects specify natural stone for its recyclability and low environmental impact.

Challenges

Supply chain constraints, environmental regulations, high processing costs, and logistical challenges are prevalent, particularly in Europe.

Summary

The natural stone industry is substantial and steadily growing—especially in Europe where heritage, quality materials, and renovation demand bolster the sector. The global stage, however, is clearly dominated by Asia-Pacific, thanks to its urbanization boom. Key European players like Italy and Spain remain significant not just regionally but also globally in terms of craftsmanship and export.

2. TYPES OF ORNAMENTAL STONES (MARBLE, GRANITE, SLATE, LIMESTONE...)

In the ornamental stone sector (some other names: architectural stone, dimension stone), the term refers to natural stones used for decorative and architectural purposes – mainly in construction, monuments, interior design, and art.

The main types of ornamental stones are:

2.1. Marble

- Composition: Metamorphic rock, recrystallized limestone (calcite/dolomite).
- Features: Fine-grained, polishable, elegant veining, variety of colours (white, black, green, pink).
- Uses: Flooring, wall cladding, sculptures, monuments, luxury countertops.
- Famous Examples: Carrara (Italy), Pentelic (Greece), Makrana (India), Rosa Portugues (Portugal).

2.2. Granite

- Composition: Igneous rock (quartz, feldspar, mica).
- Features: Very hard, durable, resistant to weathering; wide colour range (grey, black, red, blue).
- Uses: Facades, paving, memorials, countertops, stairs.
- Famous Examples: Balmoral Red (Finland), Blue Pearl (Norway), Rosa Beta (Italy).

2.3. Slate

- Composition: Metamorphic rock from shale.
- Features: Splits easily into thin sheets, resistant to weather, dark tones (grey, black, green, purple).
- Uses: Roofing, flooring, cladding, billiard tables.
- Famous Examples: Galician Slate (Spain – 90% of Europe's roofing slate), Welsh Slate (UK).

2.4. Limestone

- Composition: Sedimentary rock, mainly calcite.
- Features: Softer than marble/granite, warm beige/cream tones, can be fossiliferous.
- Uses: Facades, interior cladding, flooring, historical buildings.

- Famous Examples: Jura (Germany), Moca Cream (Portugal), Vicenza Stone (Italy).

2.5. Sandstone

- Composition: Sedimentary rock, cemented sand grains (quartz dominant).
- Features: Easy to cut/carve, earthy tones (yellow, red, brown, grey).
- Uses: Walls, paving, decorative columns, landscaping.
- Famous Examples: Yorkshire Sandstone (UK), Dholpur (India), Raj Green (India).

2.6. Travertine

- Composition: Porous variety of limestone, formed by precipitation in hot springs.
- Features: Characteristic cavities/veins, earthy colours (cream, tan, gold).
- Uses: Flooring, facades, bath areas, monuments.
- Famous Examples: Tivoli Travertine (Italy), Denizli Travertine (Turkey).

2.7. Onyx

- Composition: Banded form of chalcedony/quartz or calcitic banded stone (often used decoratively).
- Features: Translucent, striking colour bands (green, honey, red).
- Uses: Decorative panels, luxury interiors, backlit installations.
- Famous Examples: Mexican Onyx, Pakistani Green Onyx.

2.8. Quartzite

- Composition: Metamorphosed sandstone (high quartz content).
- Features: Very hard, sparkly appearance, range of colours.
- Uses: Countertops, cladding, paving.
- Famous Examples: Taj Mahal Quartzite (Brazil), White Macaubas (Brazil).

2.9. Other Decorative Stones

- Basalt (volcanic, dark, used in paving and monuments).
- Serpentine (Metamorphic, decorative stone, interior panels, sculptures)
- Tuff & Porphyry (volcanic, decorative paving, historic Roman use).
- Breccia (angular fragments cemented together, decorative walls/floors).
- Alabaster (soft gypsum stone, translucent, sculptures and small objects).

2.10. Summary

The major ornamental stones are marble, granite, limestone, sandstone, slate, travertine, onyx and quartzite with many local varieties giving each country its unique identity in the stone sector.

3. FROM QUARRY TO MARKET: THE INDUSTRIAL PROCESS

The industrial process from ornamental stone quarry to market passes through several stages.

3.1. Geological Exploration and Survey

Objective**:** Identify and evaluate deposits (marble, granite, limestone, etc.).

Activities**:**

- Geological mapping, sampling, and drilling.
- Testing for colour, texture, veining, structural integrity, fracture patterns.
- Feasibility studies (reserves, extraction cost, market demand).

3.2. Quarry planning and development

Planning:

- Decide quarry design, bench height, access roads.
- Environmental Impact Assessment (EIA).
- Permits and licenses (countries and EU).

Infrastructure setup: access roads, water/electricity supply, waste management areas.

3.3. Extraction (Quarrying)

Different techniques depending on stone type and desired block quality:

- Diamond wire saws: For marble, granite, travertine (precise, minimal waste).
- Chain saw machines: Cutting soft/medium hardness stones (limestone, marble).
- Drilling & splitting with wedges: Traditional method for slate, sandstone.
- Controlled blasting: Occasionally used but avoided in ornamental stone (causes fractures).

3.4. Block Handling and Transportation

- Blocks are cut into regular shapes.
- Heavy cranes, loaders, and trucks move them from quarry floor to stockyards.
- Blocks graded by colour, pattern, cracks, and dimensions.
- Transport to processing plants (on the island of Brač nearby, but often distant).

3.5. Primary Processing (Sawing and Slabbing)

- Gangsaws or block cutters: Slice large blocks into slabs (2–10 cm thick).
- Slab calibration: Ensures uniform thickness.
- Polishing lines: Slabs polished with abrasives (diamond, resin pads) to glossy, honed, brushed, or textured finishes.
- Waste as side product (slurry, powder, off-cuts) is managed or recycled where possible.

3.6. Secondary Processing (Finishing and Shaping)

- Surface finishes: Polished, honed, flamed, bush-hammered, sandblasted, leathered, antiqued.
- Edge shaping & profiling: For countertops, steps, windowsills.
- Special products: Ashlars, tiles, cladding panels, decorative pieces, mosaics
- Resin treatment: Some marbles and onyx reinforced with resin/glass fibre for strength.

3.7. Quality Control and Grading

- Inspection of colour uniformity, surface finish, thickness, dimensional accuracy.
- Classification of stone blocks into first, second, third class (according to cracks and other discontinuity, commercial quality).
- Testing for physical and mechanical properties (water absorption, density, compressive strength, frost resistance).

3.8. Packaging and Logistics

- Slabs packed in wooden bundles (crates).
- Tiles packed in pallets or boxes.
- Blocks sometimes shipped raw.
- Transport via trucks, rail, or containers.

3.9. Commercialization and Market

- Direct sales: From quarry companies to distributors, contractors, architects.
- Stone fairs and exhibitions: Marmomac (Italy), Xiamen Stone Fair (China), Coverings (USA).
- Distribution network: Wholesalers, stone yards, fabricators.
- End uses: Architecture, monuments, restoration, landscaping, luxury design.

Very important is sustainability trend which means recycling slurry, water treatment, optimizing quarry rehabilitation, and life-cycle assessments are growing priorities.

4. KEY STAKEHOLDERS: SMEs, ASSOCIATIONS, INSTITUTIONS

4.1. SMEs and Companies

Most of the industry is dominated by SMEs (small and medium enterprises), especially in Europe, though large integrated groups also exist.

- Quarrying Companies – extract raw blocks (often family-owned SMEs).
- Processing Companies – sawmills, polishing plants, fabricators (tiles, slabs, countertops).
- Distributors and Traders – stone yards, wholesalers, exporters/importers.
- Design and Craft Studios – stonemasons, sculptors, architectural workshops.
- Large Integrated Firms – vertically integrated groups managing quarry to processing to sales.

4.2. Associations

These bodies represent companies, lobby for favourable regulations, promote sustainability, and organize fairs.

International

- World Natural Stone Association (WONASA) – global industry network.
- ISRM (International Society for Rock Mechanics) – technical/scientific community relevant for extraction methods.
- ICOMOS Stone Committee – heritage preservation experts using natural stone.

European

- EUROROC – European Federation of Natural Stone Industries, umbrella for national associations.
- Construction Products Europe (CPE) – covers stone as a building material.

4.3. Institutions and Researchers

Provide scientific, technical, and policy frameworks.

- Universities & Technical Institutes – geology, mining, materials science, restoration.
    - e.g. University of Pisa (Italy), Polytechnic University of Madrid (Spain), NTUA Athens (Greece).
- Research Centres.
    - CTMARMOL (Spain) – technology centre for marble.
    - CEVALOR (Portugal) – technology centre for natural stone.

- Standardization & Certification Bodies
  - CEN (European Committee for Standardization) – stone testing & product standards.
  - ISO (International Organization for Standardization) – standards on natural stone.
- Government & EU Institutions
  - Ministries of Industry, Trade, and Environment (licenses, quarry permits, environmental regulation).
  - EU programs supporting innovation, sustainability, circular economy in the stone sector.

4.4. Supporting Stakeholders

- Trade Fairs & Exhibitions (major commercial platforms):
  - Marmomac (Verona, Italy) – world's leading stone fair.
  - Xiamen Stone Fair (China) – largest global fair for natural stone.
  - Coverings (USA) – North America's top tile & stone exhibition.
- Architects & Designers – specify ornamental stone in projects.
- Conservation/Heritage Authorities – select stone for monuments and restoration.
- Environmental NGOs & Local Communities – influence quarry sustainability and land use.

5. CURRENT CHALLENGES: ENERGY COSTS, CO_2 EMISSIONS, TRACEABILITY

The ornamental stone industry faces several strategic challenges that go beyond simple quarrying and finishing. Today, three of the most pressing are:

- energy costs,
- CO_2 emissions, and
- Traceability.

5.1. Energy Costs

Quarrying, sawing, polishing, and transport are highly energy-intensive**.** Energy prices in Europe (especially post-2021) rose dramatically, reducing competitiveness vs. lower-cost producers (China, India, Turkey).

Processes most affected:

- Diamond wire cutting, gangsaws, polishing lines - heavy electricity consumption.
- Diesel for quarry equipment and block/stone transport.

Impacts:

- Squeezed profit margins for SMEs.
- Some companies cutting shifts or delaying investment.

Trends/solutions:

- Shift toward renewable energy at quarries/plants (solar, wind).
- More energy-efficient cutting technologies (multi-wire saws).
- EU incentives for industrial energy efficiency projects.

5.2. CO_2 emissions and environmental Impact

Direct emissions:

- Diesel machinery in quarries.
- Transport of heavy blocks (sometimes intercontinental).

Indirect emissions:

- Electricity consumption (esp. if grid powered by fossil fuels).

Challenges:

- Ornamental stone competes with ceramics, engineered quartz, and concrete - all of which market themselves as more "controlled" or "eco-friendly".
- Pressure from green building certifications (LEED, BREEAM) requiring carbon footprint documentation.

Trends/solutions:

- Life Cycle Assessment (LCA) and Environmental Product Declarations (EPDs) for stone products.
- Recycling of slurry, dust, and offcuts (for aggregates, fillers, cement industry).
- Carbon reduction commitments (EU Green Deal → net zero by 2050).
- Development of low-impact logistics (rail transport, shipping efficiency).

5.3. Traceability

Architects, clients, and regulators increasingly demand proof of origin (ethical sourcing, environmental impact, fair labour).

Also, EU regulations on sustainable supply chains are tightening.

Challenges:

- Many stones are traded through intermediaries - difficult to verify quarry of origin.
- Risk of "stone laundering" (false labelling of origin to avoid tariffs or gain prestige).

Trends/solutions:

- Digital traceability systems (QR codes, blockchain from certify quarry to factory and to end user.
- ISO and CEN standards on labelling and testing.
- Stronger role of industry associations (e.g., EUROROC, national federations) in creating transparent certification schemes.
- Traceability becoming a competitive advantage (e.g., "100% Italian marble from Carrara").

5.4. Summary

The ornamental stone sector is under pressure to lower costs, prove sustainability, and ensure transparency. Companies that invest in clean energy, measure their carbon footprint, and adopt traceability systems will be best positioned to stay competitive in Europe and globally.

6. LEGAL AND ENVIRONMENTAL CONTEXT (EUROPEAN GREEN DEAL, TAXONOMY...)

Legal and environmental context for the ornamental stone industry in Europe are based on two pillars: European Green Deal and the EU Taxonomy**.** These two pillars are reshaping how quarrying, processing, and commercialization of stone are regulated and financed.

6.1. European Green Deal (2019–)

European Green Deal is the EU’s main strategy to reach climate neutrality by 2050**.** It directly impacts extractive industries**,** including ornamental stone. Key areas affecting stone industry are:

Climate and energy

- Target: -55% GHG emissions by 2030.
- Quarrying and processing plants → pressure to cut diesel and electricity-related emissions.
- Push for renewable energy and efficient technologies in extraction & processing.

Circular Economy Action Plan (CEAP)

- Prioritizes waste reduction and recycling.
- Quarry waste (slurry, offcuts) must increasingly be valorised (aggregates, fillers, cement additives).
- Companies expected to report resource efficiency & recycling rates.

Sustainable Products Regulation (under Ecodesign framework)

- Construction products (including stone) must demonstrate long durability, low footprint, and recyclability.
- Favourable for natural stone vs. ceramics/concrete (stone = long-lasting, low processing).

Biodiversity & Land Use

- Quarrying in Natura 2000 areas faces strict limitations.
- Operators must implement rehabilitation plans (land restoration, biodiversity offsets).

6.2. EU Taxonomy for Sustainable Finance (2020–)

A classification system defining which activities are “environmentally sustainable” and crucial for financing, subsidies, and investor credibility. Criteria relevant to stone sector:

To be “taxonomy-aligned”, stone activities must:

1. Substantially contribute to climate mitigation/adaptation (e.g., durable, low-carbon material in construction).
2. Do no significant harm **(**DNSH**)** to other environmental objectives (water, circular economy, biodiversity, pollution).
3. Meet minimum safeguards (labour, governance, human rights).

But these frames offer also some opportunities for stone:

- Natural stone scores well on durability and recyclability - can qualify as a sustainable construction product compared to ceramics/concrete.
- If companies prove low CO_2 footprint and traceability, they may access green finance, subsidies, and public procurement markets.

And put set some challenges and risks, for example:

- SMEs often lack resources for taxonomy reporting, LCA studies, and audits.
- Risk: if stone producers fail to meet taxonomy criteria, banks may classify them as “non-green”, limiting investment access.

6.3. Other Relevant EU Legislation

- Construction Products Regulation (CPR)
- Sets rules for CE marking and product declarations.
- Likely to require Environmental Product Declarations (EPDs) for stone in the future.
- Industrial Emissions Directive (IED)
- Controls dust, noise, water discharges from quarries & processing plants.
- Waste Framework Directive
- Pushes for quarry waste valorisation and proper disposal of slurry.
- Corporate Sustainability Reporting Directive (CSRD)
- Large companies (and eventually SMEs in supply chains) must disclose environmental and social performance.

These regulations have different implications for the stone industry such as:

- Higher compliance costs: More environmental reporting, monitoring, and audits.
- Competitive opportunity: If properly marketed, natural stone can be positioned as “the sustainable choice” vs. ceramics or concrete.
- Financing pressure: Only taxonomy-aligned projects attract green funding and lower interest loans.
- Innovation push: Recycling technologies, renewable energy, digital traceability becomes strategic investments.

6.4. Summary

The legal and environmental context in Europe is tightening**,** but it also gives natural stone a unique chance**:** if producers can document durability, low carbon footprint, and responsible sourcing**,** stone could be recognized as a preferred sustainable construction material under the EU Green Deal and Taxonomy.

REFERENCES

Market Research Reports & Consulting, Grand View Research, Inc., (https://www.grandviewresearch.com/)

Europe Natural Stone Market Size & Outlook, 2024-2030 (https://www.grandviewresearch.com/horizon/outlook/natural-stone-market/europe?utm_source=chatgpt.com)

Global Natural Stone and Marble Market Report 2025 Edition, Market Size, Share, CAGR, Forecast, Revenue (https://www.cognitivemarketresearch.com/natural-stone-and-marble-market-report?utm_source=chatgpt.com)

Linkedin, Global market natural stone 2025 (https://www.linkedin.com/pulse/global-market-natural-stone-2025-maksym-kurechko--xbgce?utm_source=chatgpt.com)

Global Growth Insights, Market Research Report & Consulting, (https://www.globalgrowthinsights.com/)

Slate industry in Spain - Wikipedia (https://en.wikipedia.org/wiki/Slate_industry_in_Spain?utm_source=chatgpt.com)

Construction Stone Market Report, Global Forecast From 2025 To 2033, (https://dataintelo.com/report/construction-stone-market?utm_source=chatgpt.com)

Natural Stone Market Size & Industry Share, (https://www.reanin.com/reports/global-natural-stone-market?utm_source=chatgpt.com)

THE EUROPEAN GREEN DEAL, https://www.esdn.eu/fileadmin/ESDN_Reports/ESDN_Report_2_2020.pdf

EU taxonomy for sustainable activities - Finance - European Commission, https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en

B. Crnković, Lj. Šarić, GRAĐENJE PRIRODNIM KAMENOM, Rudarsko-geološko-naftni fakultet Sveučilišta u Zagrebu, 1992.

RockChain Course:
UNIT 2.
Blockchain Fundamentals.

"Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them."

Contents

1. WHAT IS BLOCKCHAIN? ORIGIN AND EVOLUTION

1.1. Introduction

In the last years, digital technologies have become a required element for innovation and competitiveness in various industries. One of the technologies which is distinguished for its potential to bring more transparency, security and efficiency in data and process management is blockchain.

In the ornamental rock industry, where resource optimization is very important, this technology allows the recording and verification of transactions, which makes responsible resource management efficient and supports the principles of the circular economy (Crosby, Pattanayak, Verma, & Kalyanaraman, 2016; Yaga, Mell, Roby, & Scarfone, 2018).

1.2. Definition of Blockchain

Blockchain is a distributed technology that allow the storage and transmission of information in a protect, transparent, and decentralized manner. It is also known as Distributed Ledger Technology (DLT).

According to Crosby, Pattanayak, Verma, and Kalyanaraman (2016), a blockchain can be understood as a distributed public ledger of all transactions, verified by unanimity among participants. Similarly, Yaga, Mell, Roby, and Scarfone (2018) define blockchain as a distributed ledger implemented as a chain of blocks, each containing a set of cryptographically linked transactions. These features ensure that data cannot be altered without affecting the entire chain and that trust is maintained collectively by the network rather than a central authority.

Although it has become known globally through cryptocurrencies, blockchain is not limited to this field.

1.3. Origin and evolution

The origin of blockchain is closely linked to the 2008 financial crisis, which reduced public trust in traditional banking and financial institutions. In this context, Satoshi Nakamoto published the paper "Bitcoin: A Peer-to-Peer Electronic Cash System", in which he proposed a decentralized electronic payment system based on a peer-to-peer network and a distributed ledger (Nakamoto, 2008). This paper, published in October 2008, is considered the birth certificate of blockchain. A few months later, in January 2009, the Bitcoin network was launched, the first practical application of the technology. It demonstrated that it was possible to transfer money and other forms of digital value between two participants, without the need for an intermediary, such as banks or payment processors, and transactions could be validated by the agreement of network participants.

Since this first application, blockchain has known a rapid evolution, which can be divided into several stages.

Blockchain 1.0

The first stage corresponds to the period in which the technology was used almost exclusively for digital currencies. The attention was on secure and decentralized financial transactions, and Bitcoin remained the main application. This stage was referred to as Blockchain 1.0.

Blockchain 2.0

A second stage was marked by the emergence of the Ethereum platform in 2015, proposed by Vitalik Buterin. Ethereum introduced the concept of smart contracts, self-executing programs that run on the blockchain and allow the automation of complex processes, from financial transactions to supply chain management. This innovation has radically expanded the possibilities of blockchain, transforming it into an infrastructure capable of hosting decentralized applications.

Blockchain 3.0

The expansion of the use of technologies beyond the financial domain and integration into the industrial and social sectors has led to the third stage called Blockchain 3.0. As of 2019, blockchain technology has been used for product traceability, medical data security, digital identity validation or renewable energy management (Guo, 2025). Tapscott and Tapscott (2016) emphasize that blockchain has the potential to revolutionize the way companies and governments manage information and resources, through transparency and the reduction of intermediaries.

Blockchain 4.0

Today, there is talk of a fourth stage, Blockchain 4.0, which aims to integrate with other emerging technologies, such as artificial intelligence, the Internet of Things or virtual reality, emphasizing scalability, sustainability and interoperability.

Blockchain has long transcended the boundaries of the financial domain and has proven extremely valuable for resource traceability and sustainable management of material flows. In the waste management and mining industries, blockchain can be used to monitor the path of waste, certify recycling processes, and ensure compliance with environmental regulations (BlockWaste Project, 2023).

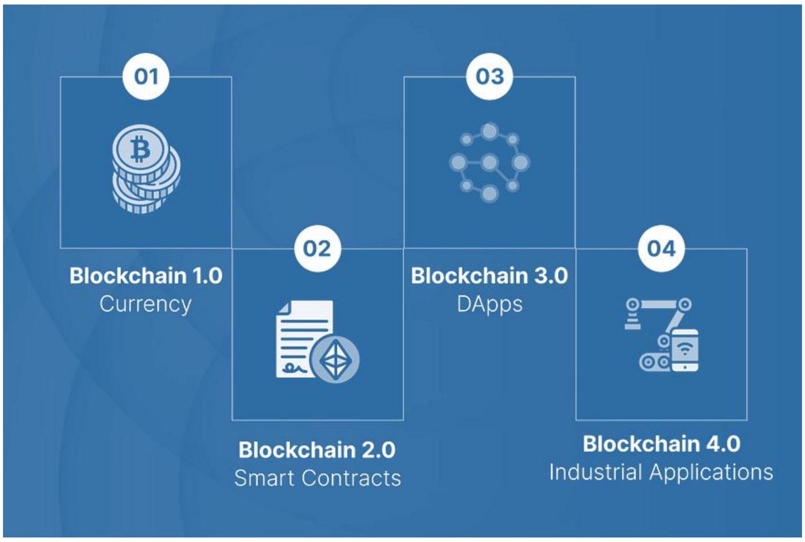

Figure 1. Evolution of Blockchain. Source: https://medium.com/coinmonks/blockchain-4-0-the-next-generation-of-blockchain-technology-78de1cac6479

As illustrated in Figure 1, the evolution of blockchain can be traced from its initial use in digital currencies (Blockchain 1.0), through the emergence of smart contracts (Blockchain 2.0) and decentralized applications (Blockchain 3.0), to its current stage of industrial applications (Blockchain 4.0), highlighting a progressive expansion of both functionality and impact.

Types of blockchain

As technology has evolved, several types of blockchain have been developed, adapted to different organizational needs. These types can be grouped into four main categories: public, private, consortium, and hybrid blockchains.

Public blockchains are completely open, anyone can participate in the network, validate transactions and view data. Relevant examples are Bitcoin and Ethereum. This type of blockchain is highly transparent, but scalability and transaction speed remain a challenge.

In contrast, private blockchains are managed by a single organization, which controls access to the network. This offers speed and efficiency, but limits access to information and the validation process. In this way, the level of transparency is reduced, since not all users can verify the data, and the degree of decentralization, since control of the network remains concentrated in the hands of a single organization.

An intermediate solution is the consortium blockchain, where several organizations collaborate to manage the network. In this case, control is divided among the participants, which provides a balance between efficiency and decentralization.

Hybrid blockchain combines elements of the previous two types. An example is IBM Food Trust, used for food traceability. It allows some data to be public, while others remain private, depending on the needs of the partners involved.

To highlight the differences between the main types of blockchain, Table 1 summarizes some essential criteria, such as accessibility, transparency, transaction speed, and level of control.

Table 1. Comparative analysis of blockchain types.

Type of Blockchain	Accessibility	Transparency	Transaction Speed	Level of Control	Examples
Public	Anyone can participate, open to all	Very high – all data is visible to participants	Lower, due to the large number of nodes and complex consensus mechanisms	Distributed – control is shared among all participants	Bitcoin, Ethereum
Private	Restricted, only authorized users	Low – access to data is limited	High – few nodes and fast validation mechanisms	Centralized – control exercised by a single organization	Hyperledger Fabric
Consortium	Limited to member organizations	Medium – data is visible among consortium participants	High – fast consensus among a limited group of nodes	Partially decentralized – control shared by several organizations	R3 Corda, Quorum
Hybrid	Mix of public and private access	Variable – some data is public, others private	Medium – balance between security and performance	Combined control: some processes open, others centralized	IBM Food Trust

Source: Adapted from Mougayar, W. (2016). The Business Blockchain. Wiley.

Since its origins in the context of the 2008 financial crisis, blockchain has rapidly evolved from a technology associated exclusively with cryptocurrencies to a digital infrastructure with complex and diverse applications. The fact that there are multiple types of blockchain allows the technologies to be adapted to different scenarios, from fully transparent public networks to private networks for corporations. Today, blockchain stands at the intersection of technological innovation and profound changes in society and the economy, with the potential to reshape the way data is managed and trust is built in the digital environment.

2. BASIC CONCEPTS: BLOCKS, CHAIN, HASH, TIMESTAMP, CRYPTOGRAPHY

To understand blockchain, it is necessary to clarify some fundamental concepts that constitute its operating mechanism. The essential technical elements that make blockchain possible include blocks, the chain that connects them, hash functions, timestamps, and cryptographic mechanisms (Yaga et al., 2018).

Blocks are units of data that contain a set of validated transactions and cryptographic hashes that link to previous blocks, thus forming immutable records in the blockchain network.

Each block in the blockchain is a digital container that stores for all time transaction data for the network. When new transactions come, they are grouped into a block. After that the network validates these transactions, the block is clammed and cryptographically linked to previous blocks. This creates a chain in which the contents of each block cannot be changed without affecting the others.

The main components of very block in a blockchain are:

- Data
- The hash of the block
- The hash of the previous block

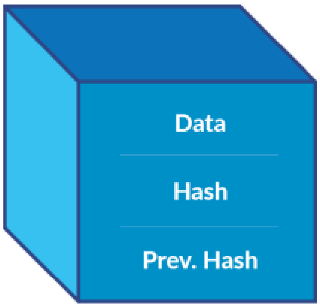

Figure 2. Components of a block in the blockchain. Source: https://mastechinfotrellis.com/hubfs/Fundamentals-of-Blockchain-Technology-Explained.pdf

Data is the most important part of the block. The data within a block can be of any type, depending on the blockchain application - from contractual agreements in smart contracts to voting records, medical information, and more, depending on the use case.

Hash of the block is a code generated based on the data in the Block. It identifies the Block and all its contents and is always unique. If the data within the Block changes in any way, the hash also changes, which is very important for the security of the Blockchain. This hash is what links one block to another, forming the durable chain.

Previous Hash is the Hash code of the previous Block. This creates the actual chain of blocks and is essential to the correctness of the blockchain. Each block includes the Hash of the previous one, making it difficult to modify the data of any block without affecting the entire chain. The first Block in the Blockchain does not contain a Previous Hash and is called the Genesis Block. The connection between the blocks is realised through cryptographic hash functions, which ensure that even a small modification in one block would alter all subsequent blocks. This mechanism guarantees immutability and strengthens trust in the blockchain system. Hashes therefore play a crucial role in ensuring the integrity and security of data.

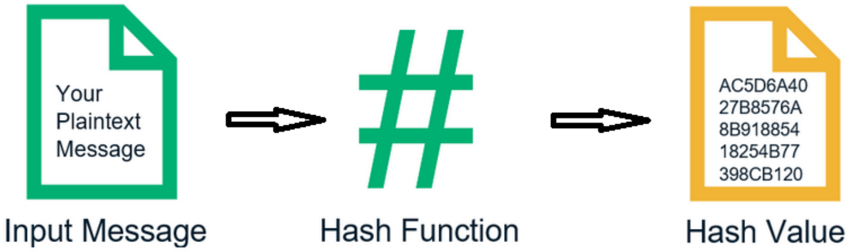

Figure 3. Cryptographic hash in action. Source: https://sectigostore.com/blog/hash-function-in-cryptography-how-does-it-work/

The **chain** is the link that connects the blocks together, so that they form a secure and unalterable sequence.

A blockchain chain is sequence of blocks, each containing a list of transactions, serving as the backbone of decentralized systems. These blocks are linked chronologically, forming a chain (Chilz, 2024).

A **timestamp** is a digital record that notes the exact moment a block was created and validated. It serves to establish the chronological order of transactions and to assurance that the information in the ledger is accurate and transparent, protected by rules that prevent subsequent changes.

Cryptography is the science of encoding data to protect it and ensure the integrity and security of transactions, prevent any third party from gaining access to the data during a communication process (Crosby et al., 2016).

Cryptography, in the blockchain, is used to protect transactions taking place between two nodes in a blockchain network. It is based on two main mechanisms: encryption (symmetric-key and asymmetric-key) and cryptographic hashing.

These mechanisms are illustrated in Figure 4, which highlights how encryption and hashing work together to secure blockchain transactions.

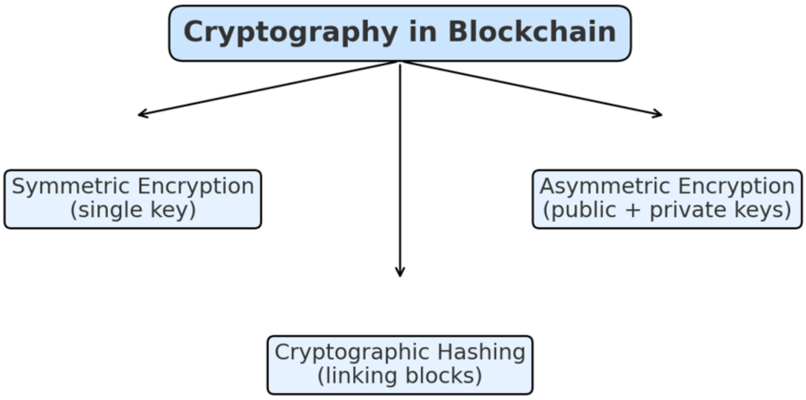

Figure 4. Crypography in Blockchain.

Symmetric key encryption uses a similar key for both encryption and decryption. The algorithm and key combine to encrypt the original sensitive information by converting the plaintext into ciphertext.

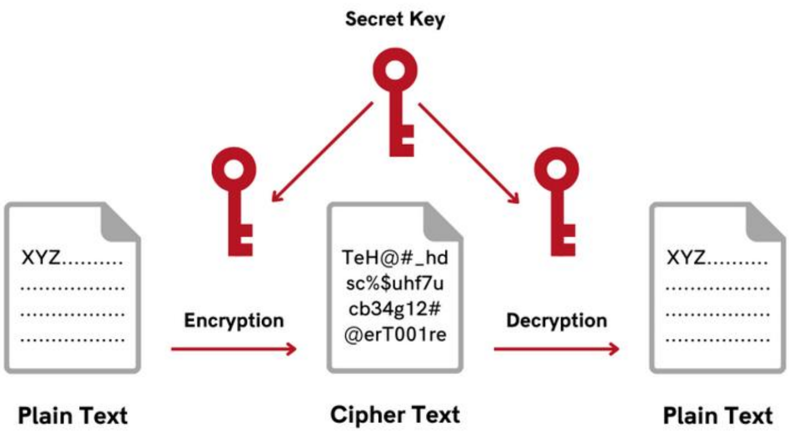

Figure 5. Symmetric-key cryptography. Source: https://blog.cfte.education/what-is-cryptography-in-blockchain/#Definition_of_Cryptography

Asymmetric encryption uses different keys, such as a public key and a private key, for encryption. The public key is used to encrypt data and can be seen by anyone else, and the private key, which is not available to everyone, is used to decrypt the data.

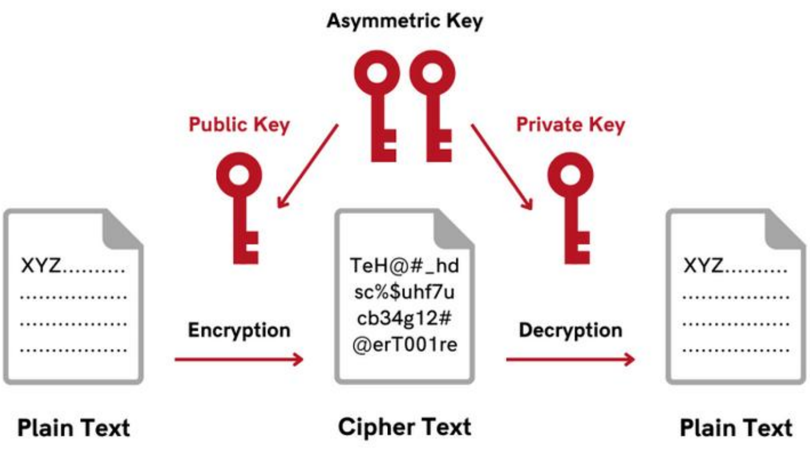

Figure 6. Asymmetric-key cryptography. Source: https://blog.cfte.education/what-is-cryptography-in-blockchain/#Definition_of_Cryptography

Cryptographic hashing converts data into unique strings, which permit for the detection of any changes and ensures the secure connection between blocks. It does not involve any use of keys, but uses a cipher to form a fixed-length hash value. Using a hash algorithm, any plain text information can be converted into a unique string of text. Regardless of the length of the input value, the hash has always a fixed length. This principle is illustrated in Figure 7, where the inputs ‘hello’ and ‘HELLO’ produce different hash values of the same fixed length.

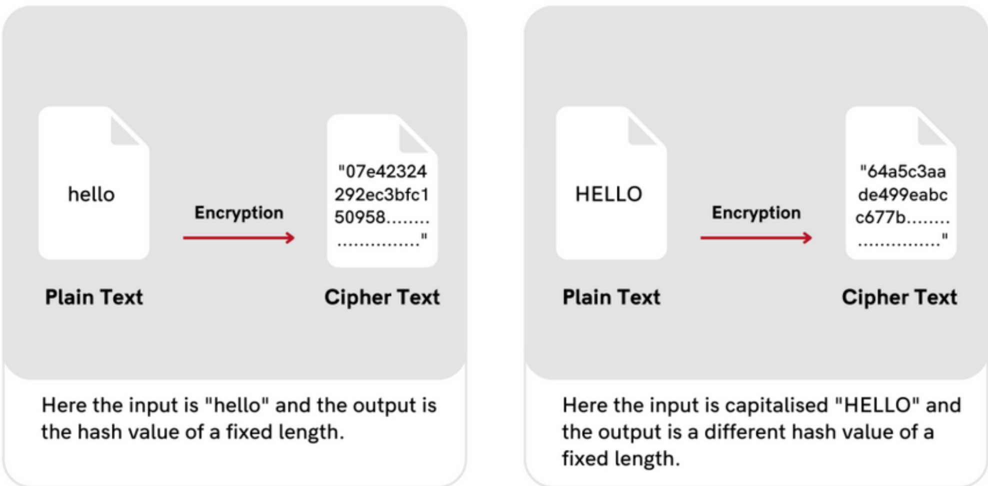

Figure 7. Hash function. Source: https://blog.cfte.education/what-is-cryptography-in-blockchain/#Definition_of_Cryptography

Using these mechanisms, cryptography ensures data integrity and confidentiality, makes transactions secure and verifiable, and gives blockchain the character of a decentralized and trusted ledger.

3. DISTRIBUTED LEDGERS AND DECENTRALIZATION

Distribute ledgers

The technological infrastructure and protocols which allow simultaneous access, validation, and updating of records in a networked database are called distributed ledger technology (DLT) (Harvard Law School Forum on Corporate Governance, 2022). In contrast to traditional databases, which are centralized and maintained by a single entity, DLT is decentralized and operates on a peer-to-peer[1] network (Crosby et al., 2016). Each participant, or node, in the network has a copy of the ledger, and any updates to the ledger are constructed and recorded independently by each node. The ledger is maintained through accords between nodes, ensuring that all copies of the ledger are identical.

DLT is the technology that is used to build blockchains, and the infrastructure is what allows users to see what changes have been made and by whom, reducing the need for data auditing, ensuring data integrity, and providing access only to those who need it. This is illustrated in Figure 8, where four nodes exchange updates to keep their ledgers identical, demonstrating how DLT maintains transparency and synchronization without a central authority

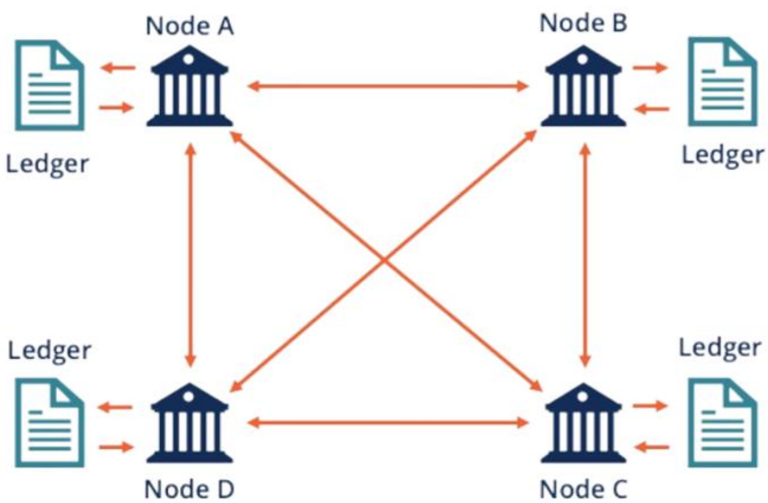

Figure 8. Distributed Ledgers. Source: https://corporatefinanceinstitute.com/resources/cryptocurrency/distributed-ledgers/

The distributed ledger is one of the key logical components of a blockchain environment. Its most notable feature is decentralization (Yaga et al., 2018).

Decentralization

[1] peer-to-peer = direct sharing of resources and information between devices or users without the need for a central authority or server

Decentralization is the core principle that conduct blockchain and distributed ledgers. Instead of having a single point of control, the network is shared among all participants. This reduces the risk of attacks because there is no single entity to put pressure on.

Decentralization reduces dependence on intermediaries, giving individuals more control over their data (Harvard Law School Forum on Corporate Governance, 2022). The decentralization of waste management systems improves local recycling and the reuse of resources, significantly reducing environmental impact compared to centralized systems.

4. SMART CONTRACTS: DEFINITION AND USES

Smart contracts are self-executing digital agreements stored on a blockchain. The contract terms are written as code and automatically enforced once the specified conditions are met, without the need for intermediaries. This automation reduces delays, prevents disputes, and ensures transparency (European Commission, EU Blockchain Observatory and Forum, 2020; Tapscott et al. 2016).

A key element of smart contracts is automation. This means that certain actions, such as updating a certificate, are performed as soon as the conditions set out in the contract are met, without the need for human intervention (Saberi et al., 2018).

Another key aspect is the immutability of smart contracts. Once a contract has been implemented on the blockchain, it cannot be modified. In this way, all parties involved can trust that the terms initially established will remain unchanged.

Another fundamental aspect is transparency. Blockchain allows all parties to view the same terms and outcomes, eliminating potential misunderstandings. In addition, by using cryptography, these contracts offer an increased level of security, reducing the risk of fraud or manipulation.

5. COMPARISON WITH TRADITIONAL DATABASES

The management of data in industries such as natural stone has traditionally relied on centralized databases. While these systems are effective for internal company records, they face limitations in multi-party ecosystems where transparency and traceability are crucial (Zheng et al., 2018).

In the case of traditional databases, control lies with a single organization or IT administrator, which confers centralized authority over the information. In addition, the stored data can be modified, deleted, or overwritten, which raises trust issues in situations where the integrity of the information is critical. Transparency is also reduced, as external parties – such as customers or regulators – often rely on reports provided by the owning organization, reports that do not always reflect the full reality. However, these databases prove effective when used within the internal workflows of a single organization, but lose their relevance when managing cross-border supply chains with multiple parties involved.

In contrast, blockchain-based databases operate on the principle of distributed ledgers. Copies of the database are stored on all participating nodes, which eliminates the risk of a single point of failure (European Commission, 2020). In addition, once a transaction has been validated, it becomes immutable, thus guaranteeing data integrity. Another major advantage is that all parties involved can verify the information directly, without depending on a central authority, which strengthens trust between actors. Moreover, blockchain allows integration with smart contracts, which makes it possible to automate processes, such as the automatic update of material passports.

To better understand the differences between the two types of databases, the following table presents a synthetic comparison between traditional and blockchain-based databases.

Table 2. Comparing Traditional Databases vs. Blockchain Databases.

Aspect	Traditional Database	Blockchain Database
Control	Centralized	Decentralized
Data Integrity	Editable	Immutable
Transparency	Limited	Shared across all
Trust Requirement	High (in authority)	Low (in code)
Automation	Requires external tools	Built-in via smart contracts

The relevance of this comparison for the natural stone industry is significant. For example, tracking the recycling processes of stone waste across borders requires the collaboration of multiple actors and a high level of trust between them. Blockchain technology provides the necessary traceability and facilitates compliance with European waste management directives. At the same time, sustainability reporting – an essential requirement for alignment with the European Green Deal and taxonomy criteria – becomes much simpler when data cannot be tampered with. Thus, blockchain not only solves the problems of transparency and trust, but also brings a major practical advantage in meeting legislative and environmental requirements.

6. USE CASES IN LOGISTICS, FINANCE, WASTE MANAGEMENT, AND MINING

Blockchain and smart contracts are not abstract technologies—they are already being applied in logistics, finance, waste management, and mining. Their integration into the natural stone sector can close material loops, reduce inefficiencies, and ensure compliance with EU sustainability policies (Saberi et al., 2018).

6.1. Use cases in logistics

Walmart, one of the world's largest retailers, was faced with a major problem: food traceability in its supply chain. Tracing the source of a contaminated product could take up to seven days, which meant high costs and risks to consumer health.

In 2017, Walmart launched the Food Trust platform, based on blockchain, together with IBM. It integrates every stage of the supply chain – from farm to processor to store – into a distributed and transparent ledger (IBM, 2017).

The result was spectacular: the time required to trace the origin of a product dropped from 7 days to just 2.2 seconds. In this way, Walmart was able to increase operational efficiency, reduce waste and, most importantly, provide consumers with more safety and trust (Walmart Global Tech, 2021 a,b).

Blockchain not only allows for the rapid identification of sources of food contamination, but also helps reduce waste, as product withdrawals from the market are targeted, only for affected batches. This significantly improves the way the recall process is managed.

The graph in Figure 9 compares traditional data management methods with blockchain-based solutions using five key criteria: traceability, trust, audit costs, food safety, and speed. The shaded areas show the performance of each method: grey for traditional methods and blue for blockchain.

Figure 9. Walmart's implementation of Blockchain Technology.

It is noted that the blue polygon (blockchain) extends much further than the gray one, which means that blockchain outperforms conventional methods in all the chapters analysed.

6.2. Use cases in finance

In the financial sector, a constant challenge is the complexity of international payments. A single transfer could pass through multiple intermediary banks, which generates delays of days, additional costs and a lack of transparency.

To solve this problem, JPMorgan launched the Interbank Information Network in 2017, later renamed Liink, based on its own blockchain infrastructure, Onyx. The network allowed participating banks to share in real time the information necessary to process payments and instantly correct errors (SA23026, 2023). Transaction processing time decreased significantly, and the introduction of JPM Coin made it possible to instantly settle between participants. The solution brought more transparency, faster services and reduced operational costs (Cousaert, 2021; Anguiano, 2023).

The Liink case is an illustrative example of how blockchain can be applied in the banking sector to solve efficiency and transparency problems. JPMorgan has demonstrated that in the area of cross-border payments, a distributed network can simplify the complicated process and generate tangible benefits on a global scale.

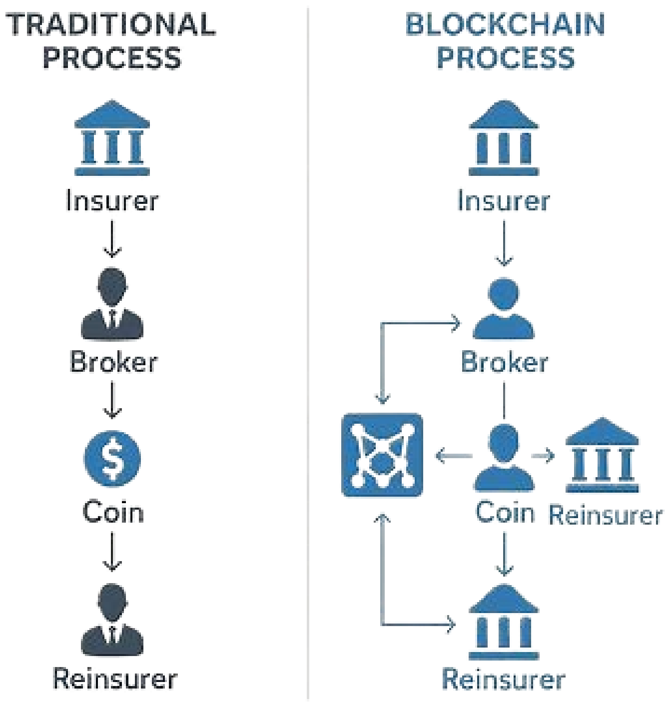

Figure 10. Differences between traditional process vs. blockchain process.

The Figure 10 highlights how traditional processes involve a linear flow, passing through multiple intermediaries one after the other, which leads to delays and additional costs. In contrast, the blockchain-based process allows all actors to access the same information in real time, reducing bottlenecks and errors. Notice how the broker, insurer, and reinsurers are connected simultaneously through the distributed ledger, which explains how this solution JPMorgan was able to reduce processing times and increase transparency in the banking network.

6.3. Use cases in waste management

A relevant example of blockchain application in waste management is the **CIRCULARPORT/CIRCULARPASS project** in Spain (Blue Room Innovation, n.d.; Taylor et al., 2020; Jovanovic, 2025; Picvisa, n.d.). Ports generate large amounts of waste from ships, and ensuring proper collection, transport, and treatment is a challenge. Traditionally, this process lacked transparency and was prone to errors or even illegal disposal.

The key aspects of this case study are summarized in Figure 11, which highlights the problem, the blockchain-based solution, and the resulting impact.

Figure 11. Blockchain for waste management: Problem–Solution–Impact in the CIRCULARPORT/CIRCULARPASS project (Spain).

As shown in Figure 11, the CIRCULARPORT and CIRCULARPASS initiatives introduced a blockchain-based traceability system that records every stage of the waste flow — from collection at the port to final treatment. All actors involved (authorities, port operators, waste treatment plants) can access the same immutable data, which increases trust and accountability.

The outcome is a system that not only complies with the EU Waste Framework Directive, but also improves efficiency by reducing paperwork and enabling real-time monitoring. Authorities gain greater control, companies can demonstrate compliance, and society as a whole benefits from more sustainable waste management.

6.4. Use cases in mining

In the mining sector, an illustrative case comes from CurrencyWorks in Canada, which developed a waste-to-energy model to power cryptocurrency mining operations (Pappas, 2021). Mining for digital assets like Bitcoin consumes enormous amounts of energy and has often been criticized for its environmental footprint.

CurrencyWorks addressed this challenge by integrating waste-to-energy plants with blockchain mining infrastructure. Municipal waste is converted into energy, which directly powers crypto-mining facilities. The blockchain network records both the energy generation process and its use, ensuring full transparency and compliance with environmental regulations.

Figure 12 illustrates this process, showing how waste is transformed into energy that powers mining activities, while blockchain ensures transparency and sustainability compliance.

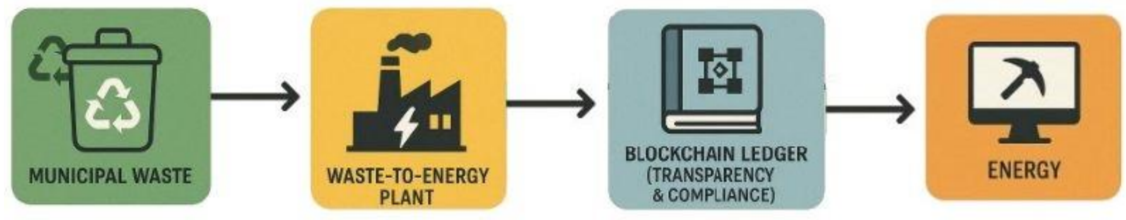

Figure 12. Waste-to-energy process powering blockchain mining (CurrencyWorks case study).

The approach shows how blockchain can be part of a circular economy solution, transforming a waste problem into a resource while also reducing carbon emissions (Taylor et al., 2020; Jovanovic, 2025; Picvisa, n.d.). It highlights the potential of blockchain not only to improve traceability and accountability, but also to support innovative, eco-friendly business models in resource-intensive industries.

The four case studies discussed above can be compared across sectors. Table X provides a recap of the use cases, highlighting the main applications, benefits, and references.

Table 3. Use Cases of Blockchain in Different Sectors.

Sector	Case Study	Highlights
Logistics	**Walmart & IBM Food Trust**	Blockchain for food supply chain traceability; reduced origin tracking time from 7 days to 2.2 seconds; improved food safety and efficiency
Finance	**JPMorgan – Liink**	Cross-border payments on distributed ledger; 400+ banks joined; faster transactions, transparency, JPM Coin for settlements
Waste Management	**CIRCULARPORT / CIRCULARPASS (Spain)**	Blockchain traceability of ship-generated waste; compliance with EU Waste Directive; increased transparency among authorities and treatment plants
Mining	**CurrencyWorks (Canada)**	Waste-to-energy model powering crypto mining; blockchain ensures transparency and environmental compliance; example of circular economy innovation

As shown in Table 3, blockchain generates value across different industries by improving transparency, efficiency, and trust. While the specific applications differ, the underlying principle remains the same: decentralized and immutable records strengthen accountability.

REFERENCES

Anguiano, T. D. (2023). The state of art, opportunities and challenges of blockchain in the insurance industry: A systematic literature review. *PMC*.

Blue Room Innovation. (n.d.). *CircularPort and CircularPass: Leveraging blockchain to promote the circular economy*. European Circular Economy Stakeholder Platform. Retrieved August 26, 2025, from https://circulareconomy.europa.eu/platform/en/good-practices/circularport-and-circularpass-leveraging-blockchain-promote-circular-economy

Chiliz (2024, August 2027) What is a Chain in Blockchain Technology? Retrieved August 18, 2025, from https://www.chiliz.com/what-is-a-chain-in-blockchain-technology/

Cousaert, S., Vadgama, N., & Xu, J. (2021). Token-based insurance solutions on blockchain. *arXiv*.

Crosby, M., Pattanayak, P., Verma, S., & Kalyanaraman, V. (2016). Blockchain technology: Beyond bitcoin. *Applied Innovation Review, 2*(6–10). https://j2-capital.com/wp-content/uploads/2017/11/AIR-2016-Blockchain.pdf

European Commission. (2020, February 19). *A European strategy for data* (COM(2020) 66 final). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX%3A52020DC0066

European Commission, EU Blockchain Observatory and Forum. (2020). *Smart contracts: Legal challenges and opportunities* (Final report). Publications Office of the European Union. https://blockchain-observatory.ec.europa.eu/document/download/53a0aeb4-d144-4054-841e-dc169b44f94d_en?filename=SmartContractsReport_Final.pdf

Guo, H. (2025). The impact of blockchain technology and smart contracts. *Nature*.

Harvard Law School Forum on Corporate Governance. (2022). Blockchain in the banking sector: A review of the landscape and opportunities.

IBM. (2017, December 14). Walmart, JD.com, IBM and Tsinghua University launch a blockchain food safety alliance in China. *IBM Newsroom*. Retrieved August 21, 2025, from https://newsroom.ibm.com/2017-12-14-Walmart-JD-com-IBM-and-Tsinghua-University-Launch-a-Blockchain-Food-Safety-Alliance-in-China

Jovanovic, D. (2025, April). Blockchain and sustainable waste management: A deep dive. Diversys. https://www.diversys.com/white-papers/blockchain-and-sustainable-waste-management-a-deep-dive/

Mougayar, W. (2016). *The business blockchain: Promise, practice, and application of the next Internet technology*. Hoboken, NJ: Wiley.

Nakamoto, S. (2008). *Bitcoin: A peer-to-peer electronic cash system*. https://bitcoin.org/bitcoin.pdf

SA23026. (2023). How JP Morgan Chase leverages blockchain technology to modernize financial services. *AABRI Manuscript*.

Pappas, A. (2021, June 17). *Canada's energy sector could win at green crypto mining*. EnergyNow.ca. https://energynow.ca/2021/06/canadas-energy-sector-could-win-at-green-crypto-mining-alex-pappas/

Picvisa. (n.d.). Blockchain technology for sustainable waste management. Picvisa. Retrieved August 23, 2025, from https://picvisa.com/blockchain-technology-for-sustainable-waste-management/

Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2018). Blockchain technology and its relationships to sustainable supply chain management. *International Journal of Production Research*, *56*(1-2), 2117–2135

Tapscott, D., & Tapscott, A. (2016). *Blockchain revolution: How the technology behind bitcoin is changing money, business, and the world*. New York, NY: Penguin.

Taylor. P., Steenmans, K., & Steenmans, I. (2020) Blockchain Technology for Sustainable Waste Management. Front. Polit. Sci. 2:590923. doi: 10.3389/fpos.2020.590923

The Geneva Association. (2023). DeFi insurance: Blockchain-based insurance and its potential.

Walmart Global Tech. (2021, June 14). Blockchain in the food supply chain. *Walmart*. Retrieved August 21, 2025, from https://tech.walmart.com/content/walmart-global-tech/en_us/blog/post/blockchain-in-the-food-supply-chain.html

Walmart Global Tech. (2021, November 30). Blockchain in the food supply chain – What does the future look like? *Walmart*. Retrieved August 19, 2025, from https://tech.walmart.com/content/walmart-global-tech/en_us/blog/post/blockchain-in-the-food-supply-chain.html

Yaga, D., Mell, P., Roby, N., & Scarfone, K. (2018). Blockchain technology overview. *NIST Interagency/Internal Report (NISTIR) 8202*. National Institute of Standards and Technology. https://doi.org/10.6028/NIST.IR.8202

Zheng, Z., Xie, S., Dai, H.-N., Chen, X., & Wang, H. (2018). Blockchain challenges and opportunities: A survey. *International Journal of Web and Grid Services*, *14*(4), 352. https://doi.org/10.1504/IJWGS.2018.095647

RockChain Course:
UNIT 3.
Circular economy in the context of natural stone.

"Funded by the European Union. However, the views and opinions expressed are those of the authors alone and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor the EACEA can be held responsible for them."

Erasmus+

Contents

1. DEFINITION AND PILLARS OF THE CIRCULAR ECONOMY (REDUCE, REUSE, RECYCLE)

Definition of the circular economy for natural stone

The circular economy aims to prevent waste and pollution. Used natural stone should remain in the cycle and be regenerated throughout its entire life cycle. It moves the industry away from a linear "extract-use-dispose" model, in which raw stones are extracted, processed, used and finally disposed of, towards a closed-loop system. In this system, every phase – from extraction and processing to construction, demolition and reuse – focuses on increasing the value of natural stone, reducing environmental impact and conserving finite geological resources.

Pillars of the circular economy for natural stone

1. Reduce

Minimizing the use of materials and energy in every phase of stone production is the cornerstone of the "reduce" pillar. By optimizing processes and designs, the natural stone industry can drastically reduce waste, lower CO2 emissions and preserve quarries.

- Precision cutting and digital templates to adapt the stone exactly to specifications
- Design for minimal waste through modular panels and standardized dimensions
- Use of lean manufacturing techniques to optimize water and energy consumption
- Preference for local sources of supply to reduce transport distances and associated emissions

2. Reuse

Extending the life of natural stone by maintaining its form and function in new applications prevents the extraction of new raw materials and landfill disposal. The "reuse" pillar emphasizes the dismantling, refurbishment and repurposing of intact stone elements.

- Deconstruction protocols for the careful dismantling of stone facades, floors, countertops, masonry, kerbstones and paving stones
- Certification and marketplaces for reclaimed stone to ensure quality and traceability
- Creative adaptation of recycled slabs and workpieces to new architectural or design features
- Partnerships with demolition companies to extract stone elements from the waste stream

3. Recycling

If stone cannot be reused in its original form, its value is recovered as a secondary raw material through mechanical recycling processes. The recycling pillar transforms used natural stone into new building materials or industrial raw materials.

- Crushing of residual pieces and demolition rubble into aggregates for concrete, road sub-base or landscaping
- Production of stone flour as a filler for mortar, ceramics and paints
- Upcycling of fine stone dust as mineral additives in composite materials or soil stabilizers
- Closing the loop by reintegrating recycled rock fractions into new manufacturing processes

By implementing these three pillars – reduce, reuse and recycle – natural stone is transformed from a disposable resource into a circular material, protecting our geological heritage and promoting sustainable development.

2. FROM LINEAR TO CIRCULAR MODELS: CHALLENGES AND BENEFITS

From linear to circular models: challenges and benefits for natural stone

The transition from the traditional "extract-use-dispose" approach to a circular paradigm in the natural stone sector requires a rethink at every stage of the stone life cycle. While this shift may be complex, it opens up environmental and economic opportunities that far outweigh the hurdles.

Challenges

- Technology and infrastructure. The development of facilities for crushing, cleaning and sorting stone waste on site requires significant investment and specialized equipment.
- Economic viability. The upfront costs of dismantling, certifying recovered materials and return logistics can deter players focused on short-term returns.
- Supply chain complexity. The tracking and tracing of recycled or reused stone via digital platforms is still in its infancy, which makes quality assurance and material transparency difficult.
- Design and specification. Architects and engineers must adapt standard details to account for differences in size, surface finish and tolerances of reused stone elements.
- Gaps in regulations and standards. In many countries, building regulations and procurement guidelines lack clear guidelines for the approval of reused or recycled natural stone.

Benefits

- Lower environmental impact. Lower extraction rates conserve geological reserves and protect habitats in the vicinity of quarries.
- Long-term cost savings. Diverting stone from landfills and using locally recovered materials can reduce waste disposal fees and transport costs.
- Improved brand and market positioning. Projects that pursue circular economy strategies attract environmentally conscious customers and often qualify for sustainability certifications.
- Resilience and resource security. Establishing a closed loop for stone supply reduces risks associated with raw material shortages and price fluctuations.
- Promotion of innovation. The demand for circular solutions promotes new business models – such as stone leasing or take-back systems – that can lead to diversification of revenue streams.

Table 1. Comparative overview.

Aspect	**Linear model**	**Advantages of the circular model**
Resource consumption	Continuous extraction of untouched natural stone	Minimized through reuse and recycling
Waste	High quantities of waste and rubble	Closed cycles reduce landfill waste
CO2 balance	Increased emissions due to transport	Smaller footprint thanks to local recovery
More	One-time value creation	Extended value through multiple life cycles
Regulatory risk	Dependence on new extraction permits	Alignment with waste management incentives

The introduction of a circular economy concept in the natural stone industry not only addresses urgent environmental concerns, but also paves the way for resilient, innovative and economically sound practices.

3. CIRCULAR PRACTICES IN EXTRACTION, PROCESSING AND PRODUCT DESIGN

Reducing waste and protecting ecosystems starts in the quarry. By rethinking the way we extract rock from the earth, we are creating the conditions for a true circular economy.

- Precision mining: Use of drone-controlled surveying and diamond wire saws to extract blocks, reducing waste by up to 30%.
- Water recirculation systems: Collection and treatment of runoff and process water on site, reducing freshwater consumption by 60%.
- Integration of renewable energies: Crushers, conveyor belts and lighting in the quarry are powered by solar or wind energy systems.
- Progressive renaturation: Restoration of biodiversity by backfilling the mined areas with sorted spoil and native plants during extraction.
- Modular block planning: Dividing extraction into smaller, demand-oriented zones to avoid over-extraction and minimize transport routes.

Transformation

In manufacturing plants and workshops, every stone chip and every drop of mud have value. Intelligent processing keeps these by-products in play.

- Digital templates and cutting optimization: Use of 3D scanning and CAM software so that multiple parts can be produced from a single raw plate, reducing waste.
- Closed slurry cycle: Collection of the stone dust/water mixture from saws and grinding machines, separation of solids for recycled aggregates and clarification of the water for recirculation.
- On-site crushing plants: Convert board scraps, offcuts and dismantled fragments into sorted aggregates for new stone composites or road sub-base.
- Energy-efficient machines: Retrofit saws and grinding machines with frequency converters and regenerative brakes to reduce power consumption.
- Material sorting plants: Use conveyor belts and optical scanners to separate unusable parts from high-quality natural stone and send them for targeted reuse.

Product design

Design decisions determine how long stone lasts and how easily it can be returned to a new cycle. Today's well-thought-out details open up tomorrow's materials.

- Design for disassembly: Specify mechanical anchoring systems (clamps, dowels, brackets) instead of mortar cast on site so that slabs can be removed cleanly.
- Standardized modules: Use a limited selection of slab sizes and thicknesses to simplify later adaptation, reuse or reconfiguration.
- Material passports: Attach QR codes or RFID tags to stone elements that record origin, surface treatment and repair history to simplify verification.

- Templates for adaptive reuse: Create design guidelines that show how old worktops, cladding or paving stones can be upcycled into furniture, mosaics or garden features.
- Take-back and leasing models: Work with suppliers to offer stone on a lease basis and guarantee return and take-back at the end of its useful life for reprocessing.

4. RECYCLING OF STONE WASTE: AGGREGATES, FILLERS, DECORATIONS, ETC.

By recycling stone waste, offcuts, rubble and dust are turned into high-quality secondary raw materials. This approach keeps many tonnes of stone rubble out of landfills, reduces the demand for new stone and opens up new business opportunities.

Aggregates
Crushed stone fragments and construction waste are durable, cost-effective aggregates for civil engineering and building construction.

- Subbase for roads and pavements
- Coarse aggregates for concrete and mortar
- Backfill material for trenches and retaining walls
- Sub-drainage systems and filter beds
- Landscaping elements (gravel paths, decorative gravel)

Fillers
Stone dust and fine powders can replace or supplement conventional mineral fillers and improve the mechanical and thermal properties of various products.

- Paints, coatings and primers (improved abrasion resistance)
- Polymer and rubber composites (fire resistance, rigidity)
- Sealants, putties and joint fillers (dimensional stability)
- Asphalt mixtures (stone mastic asphalt)
- Paper and plastics (opacity and filling power)

Decorative and architectural applications
Larger slabs and uniquely veined off-cuts unlock creative design applications, giving waste stone a second life in aesthetic contexts.

- Mosaic and inlay tiles for walls and floors
- Custom-made furniture panels, benches and table tops
- Garden ornaments, stepping stones and edging
- Wall cladding panels in various colours and textures
- Artistic sculptures, signage and accent walls

Engineered Composites and Advanced Products
By mixing stone residues with binders or other industrial by-products, technical materials with customized properties are created.

- Recycled quartz or marble surfaces (crushed stone + resin)
- Prefabricated cladding panels with recycled aggregates
- Gypsum-stone plasters and panel backs (dust + gypsum)
- 3D-printed formwork made from stone-cement slurry

- Soil stabilisers and cement bricks with stone flour

Table 2. Comparative overview

Recycling route	Input material	Starting product	Main advantage
Additives	Crushed chunks and rubble	Road sub-base, concrete aggregates	Structural strength; landfill avoidance
Fillers	Fine stone dust and powder	Paints, plastics, sealants	Improved durability; cost savings
Decorative elements	Intact remnants and slabs	Mosaics, furniture, cladding	Unique aesthetics; market stimulation
Technical composites	Powder mixed with binder	Worktops, panels, printed formwork	Customisable properties; circular economy

The recycling of stone waste not only strengthens the circular economy in construction, but also drives innovation in materials science, design and supply chain logistics.

5. CE AND DIGITIZATION: TRACEABILITY, DATA, LIFE CYCLE MONITORING

Digital technologies are opening up new opportunities for the circular economy in the natural stone sector. By collecting and analyzing information throughout the entire life cycle of the stone – from the quarry to the end of its use – stakeholders can make smarter decisions, ensure material integrity and close the loop more effectively.

Traceability

Traceability ensures that every slab, tile or solid piece has a verifiable history in terms of origin, processing and ownership. This transparency strengthens confidence in recycled or reused stone.

- QR codes and RFID tags
  Apply permanent markings to crates or individual slabs to record the date of extraction, the location of the quarry and batch details.
- Blockchain registers
  Use immutable ledgers to document transfers between quarry, manufacturer, distributor and reseller to prevent fraud and greenwashing.
- Geographic information systems (GIS)
  Map active and historical quarry locations and link digital terrain models to extraction permits and restoration plans.
- Digital material passports
  Create a uniform data file for each stone element that records its properties, surface finish and maintenance measures ( ).

Data

Collecting raw data is only the first step. A robust data management framework converts diverse inputs into actionable insights, driving efficiency gains and improving material recovery.

- Centralised cloud platforms
  Aggregate quarry throughput, manufacturing yields and construction site installations in a scalable repository.
- IoT sensors
  Monitor water quality in slurry loops, machine uptime and environmental conditions in the quarry to optimise resource utilisation.
- Building Information Modelling (BIM) integration
  Link metadata about stone elements to project models to create accurate cutting lists and minimise waste.
- Artificial intelligence and analytics
  Identify patterns in waste generation, predict maintenance needs, and recommend process adjustments to improve yield.

- Life cycle assessment (LCA)
  Automate the calculation of the carbon and water footprint for each product variant and make environmentally friendly design decisions.

Life cycle monitoring

End-to-end life cycle monitoring tracks the performance, maintenance and reusability of stones, extending their service life and simplifying subsequent recovery.

- Digital twins
  Create virtual replicas of stone installations to simulate stress, weathering and staining over time.
- Remote monitoring
  Use drones or stationary cameras to inspect facades and detect cracks, erosion or biological growth before major repairs are required.
- Predictive maintenance notifications
  Set threshold-based alerts for maintenance schedules, surface protection system reapplication or joint resealing to maintain aesthetic and structural integrity.
- End-of-life planning dashboards
  Visualize when and where stone elements reach their replacement age and trigger take-back requests or upcycling routes.
- Portals for stakeholder collaboration
  Provide architects, contractors and recovery companies with a common interface for submitting bids for recovered stone groups and planning demolition work.

The use of traceability, data management and life cycle monitoring not only increases the sustainability of natural stone but also creates new value streams – transforming a traditional industry into a digitally supported circular ecosystem.

6. EU CONTEXT: GREEN DEAL, ACTION PLAN FOR THE CIRCULAR ECONOMY, TAXONOMY

The political landscape in Europe is rapidly evolving to embed sustainability at all levels of the built environment. Stakeholders in the natural stone industry must align the extraction, processing and use of their products with three fundamental initiatives: the European Green Deal, the Action Plan for the Circular Economy and the EU Taxonomy for Sustainable Activities.

European Green Deal

The European Green Deal sets out an ambitious roadmap for the EU to become climate neutral by 2050 while promoting biodiversity and resource efficiency. For the natural stone sector, this means

- Reducing greenhouse gas emissions in quarries and during processing through the use of renewable energies and energy-efficient machinery.
- Restoring former extraction sites as part of the Biodiversity Strategy by redesigning the extracted areas and reintroducing native plants.
- Integrating stone into low-carbon construction methods through the Sustainable Products Initiative, which aims to promote durable, low-maintenance and recyclable materials.
- Taking advantage of the renovation wave to stimulate demand for durable stone facades and floors that extend the life of buildings.

Action plan for the circular economy

The Circular Economy Action Plan (CEAP) published in 2020 accelerates Europe's transition from a disposable model to a recycling model. The most important measures affecting natural stone include:

- Sustainable product policy
  - Introduction of Product Environmental Footprint (PEF) regulations for building materials, enabling a comparison of the CO2 and water footprints of stone.
  - Creation of material passports as part of the upcoming Construction Products Regulation to track stone batches from quarry to demolition.
- Waste Framework Directive
  - Classification of stone waste as potential secondary raw materials instead of inert waste, facilitating the approval of crushed aggregates.
  - Obligation for Member States to set high recycling targets for construction and demolition waste, including natural stone fractions.
- Digitisation of supply chains

- Mandatory interoperability of traceability platforms so that recovered stone can be certified and marketed across borders.

EU taxonomy for sustainable activities
The EU taxonomy is a uniform classification system that defines which economic activities contribute significantly to environmental objectives without significantly affecting others.

The natural stone industry can be classified under two main categories:

Table 3. EU taxonomy for sustainable activities

Taxonomy objective	**Activity**	**Key technical criteria**
Climate change mitigation	Extraction and processing of stone	≤ 100 g CO_2e/MJ energy consumption; share of renewable energies ≥ 30%
Circular economy	Manufacture of construction products	≥ 70% of waste is recycled on site; digital product passport with life cycle data

To be considered taxonomy-compliant, stone companies must:
- Demonstrate compliance with strict emission limits during extraction and production.
- Submit robust waste management plans that recycle residual materials into aggregates or fillers.
- Provide digital evidence (e.g. material passports) of sustainable sourcing, treatment and disposal.

Aligning natural stone practices with these three pillars ensures compliance with legal requirements, improves market access for "green" projects and positions the sector at the forefront of sustainable construction in Europe.

REFERENCES

Action Plan for the Circular Economy – European Commission

RockChain Course:
UNIT 4.
Blockchain applied to waste management.

"Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them."

Contents

1. WASTE STREAMS IN ORNAMENTAL STONE PROCESSING: TYPES AND DESTINATIONS

1. 1 Introduction

In Europe, the ornamental stone industry is seen as a strategic activity in some regions. It is associated with cultural and architectural heritage, as well as with the construction sector, decoration and more recently sustainable design. The extraction and transformation of materials from natural stone inherently involve a material waste generation, therefore this is one of the key challenges for the industry in terms of sustainability.

Every phase of the process from land surface preparation to marketing the object produced entails lost materials, which is a factor largely categorised historically as unavoidable or managed by traditional methods (land fill, land fill etc). Nowadays it is possible to appreciate the waste incurred by the ornamental stone industry as an opportunity for innovation, valorisation and traceability due to new emerging technologies, including digitisation and blockchain, within the context of the European Green Deal and the Circular Economy Action plan (European Commission, 2020a). This unit will explore the waste types, estimated quantities and existing and potential waste destinations, chiefly those related to circular practices.

1.2 Types of Waste in Stone Processing

The ornamental stone value chain is responsible for different waste types, which differ in form, composition and potential reuse. This is waste can be classified into five categories:

1. **Overburden or plant and mineral covering:**

   This waste originates from the topsoil (soils, clays, sands) that must be stripped away before reaching a mining face. Although inert material, it can cause stability issues if not dealt with appropriately. It may be reused as landscaping restoration or as part of a backfilling process if proper plans are developed.

2. **Extraction waste:**

   A volumetric expulsion of rock cannot be utilized as beneficial blocks or values through blasting, wire sawing or just sawing the material. Natural cracks, fissures or mineralogical heterogeneity cause many blocks to be waste at the quarry for structural or aesthetic reasons. At least 20-30% of the extracted stone is estimated as waste at the quarry (LIFE-ZSW, 2024).

3. **Slurry and Fine Debris from Cutting (sludge, marbrettola):**

One of the most frequent and aggravating forms of waste is the mixture of water, abrasives, calcium carbonate particles and oils produced when cutting blocks into slabs, either with discs or wires. This slurry is classified as semiliquid waste and typically ends up in a pond or incorporated as hazardous waste if they contain metals or chemicals. Studies suggest sludge can be anywhere between 22 % and 37 % of the initial volume of the block (Chen et al. 2023).

4. Fragments, waste, and endcuts:

When sizing, sizing, or cutting slabs, edges, corners, irregular off cuts or broken pieces are created. These materials will be reused, crushed, or disposed of. Even though they may visually appear to be waste in many instances they retain the mineral composition of the final product, and so are recoverable in other sectors.

5. Auxiliary waste (packaging, transport, tooling):

Waste management must also include materials linked to the logistics process: woods from pallets, plastic wrap, metal or fabric wastes. Despite their volume looking relatively small, they include substances that can alter the sustainability profile and must be managed under a general waste legislation (Directive 2008/98/EC).

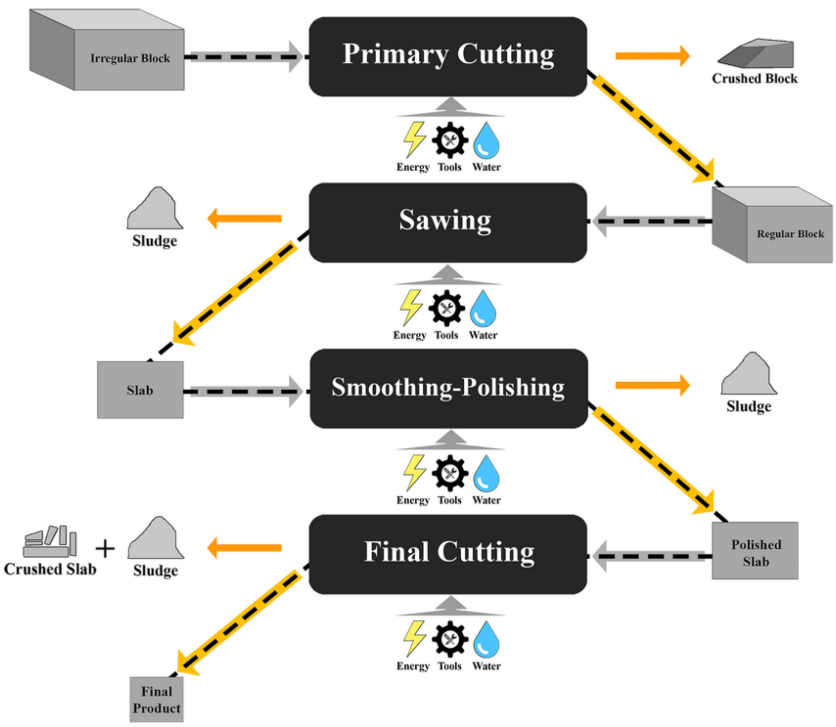

Figure 1. Types of Waste in Stone Processing. Source: https://www.researchgate.net/figure/Schematic-overview-of-the-dimension-stone-processing-procedure_fig3_353943463

1.3 Estimated Waste Volumes

The scale of the challenge becomes obvious when we look at some of the sectoral studies:

- In Italy it is estimated that up to 65 % of quarried ornamental stone material is lost as waste across the entire production process (Jalalian et al., 2021).
- In Spain, the DAPcons project on Environmental Product Declarations (RCP004 for natural stone), developed by the Institute of Construction Technology (ITeC) in collaboration with centers such as the CTM, indicates that waste and sludge generated during the processing of natural stone, may be between 200 % and greater than 200 % in weight than the final product, depending on the type of stone and the cutting method used (DAPcons, 2021).
- In the Piedmont region of Italy, a single industrial plant recorded over 37,000 tonnes of sludge each year from cutting marble (Piedmont Study, 2021).
- At a European level, it is estimated that more than 10 million tonnes of waste is produced annually from the stone sector as sludge, offcuts and chips (Eurostat, 2022).

These figures not only show the environmental impact but also show the potential for recovery of these materials if appropriate traceability, sorting and processing technologies are implemented.

1.4 Current waste destinations and emerging trends

1.4.1 Landfilling and temporary storage

There are laws increasingly limiting landfilling activity, but it still occurs, especially in rural areas or places with minimal institutional control. Sludge is placed in ponds or allowed to dry out. The risk of infiltration or erosion are present if the sludge is not managed in a relatively targeted way.

1.4.2 Environmental restoration and backfilling

Inert waste (overburden, fractured stones) can be used to backfill the void left by mining and create berms or fill in slopes if the closure plan allows for it in the restoration plan approved by the mining authorities.

1.4.3 Recycling and industrial symbiosis

Several examples exist of successful projects using ornamental stone waste for:

- Light concretes and special mortars.
- Producing cement as a substitute for primary limestone.
- Fillers for resins, ceramics or polymers as demonstrated by the LIFE ZSW project.
- It is used as limestone amendments in agriculture or in water treatment (experimental application).

1.4.4 Creative or artisan reuse

Irregular pieces can be reused as:

- Landscaping paving stone.

- Street furniture or sculptures.
- Chipboard panelling for sustainable interiors.

1.4.5 Energy and digital valorisation

Although it is still in its infancy, there is an interest in assessing how waste data, traceability and quality data can feed into digital material passports or be integrated as part of a blockchain system of rewards (see blocks 3 and 4).

1.5 Circular economy as a strategic framework

Circular economy is sometimes presented not only as an environmental option, but as a European industrial option (European Commission, 2020a). In the case of the stone sector:

- The waste is reinterpreted as secondary resources.
- Traceability and digitalisation (blockchain, IoT) provide chances to integrate these wastes into secure industrial flows.
- It promotes the creation of new jobs in sorting, classification, design of recycled products or in maintenance of the data.
- The carbon footprint is diminished from the reduced primary extraction.

Getting to know these flows and modern management of them is key for training technicians of the future in quarries, cutting plants, recovery centres or public entities.

2. LEGAL OBLIGATIONS AND REPORTING REQUIREMENTS IN WASTE MANAGEMENT

2.1 European Legal Framework

The Waste Framework Directive (Directive 2008/98/EC) is a key pillar of waste regulation in the EU. It provides definitions, such as waste, by-product, end-of-waste, and introduces a legally enforceable waste hierarchy, as follows: prevention, preparation for reuse, recycling, other recovery (including energy recovery) and disposal (European Parliament & Council, 2008). The waste hierarchy underpins all waste considerations. The waste hierarchy is particularly pertinent to the ornamental stone industry, which produces both inert and semi-liquid waste streams.

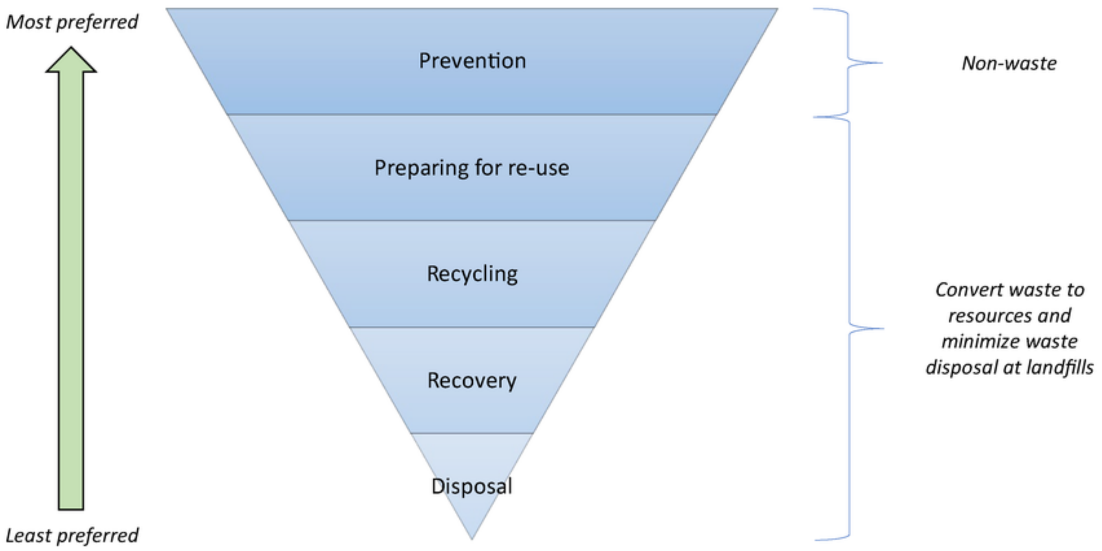

Figure 2. European Legal Framework. Source: https://www.researchgate.net/figure/The-five-step-waste-hierarchy-of-the-European-Union-Waste-Framework-Directive_fig1_368495266

The directive also reiterates the polluter pays principle and the concept of extended producer responsibility. This means that those generating waste must take responsibility for its treatment and costs—regardless of the fact that costs or treatment might have been outsourced (European Commission, 2020a). This responsibility extends to the actual materials produced during the extraction and transformation process, packaging and the materials handling process, and the economies of transport and storage.

The Waste Framework Directive was further revised in 2018 (Directive (EU) 2018/851) to include the requirement for economic instruments (landfill taxes, pay-as-you-throw schemes, extended producer responsibility systems) to promote waste minimization and circular practices (European Commission, 2020a).

2.2 Specific Legislation for Extractive and Stone Industries

2.2.1. Extractive Waste Directive (Directive 2006/21/EC)

This directive is particularly important in the ornamental stone sector, as it covers the management of waste from mining industries, including quarrying operations. Operators must create a Mining Waste Management Plan (EWMP) detailing strategies for reducing, monitoring and eliminating waste. This plan requires approval from the environmental authorities and must be updated regularly (European Commission, 2019).

Annex II of this directive also establishes specific requirements for inert waste, such as marble scraps or stone fragments, which must be managed meticulously to prevent damage to the natural environment or water pollution.

2.2.2. Landfill Directive (Directive 1999/31/EC)

This law regulates the disposal of waste in landfills, differentiating between hazardous, non-hazardous and inert waste. Although most stone waste is inert, poor management, especially of sludge containing chemical additives, may contravene landfill design or admission criteria (European Parliament and Council, 1999). The directive also imposes strict limits on the biodegradable waste that can be deposited in landfills and encourages its treatment prior to disposal.

2.2.3. Industrial Emissions Directive (Directive 2010/75/EU)

When a rock processing plant is considered a large industrial facility, it is subject to the IED Directive, which requires a permit for integrated pollution prevention and control (IPPC). This covers regulations on emissions to air, water and land, as well as on waste production and management (European Parliament and Council, 2010).

2.2.4. Environmental Management Systems: EMAS (Regulation 1221/2009)

Although optional, the Community Eco-Management and Audit Scheme (EMAS) is highly recommended for companies working in stone processing. It promotes the implementation of environmental accounting and simplifies the reporting of traceable and clear waste data, in line with the objectives of the circular economy (European Commission, 2020b).

2.3 Waste Reporting and Traceability Obligations

All European Union member countries are required to ensure that waste generators:

- Classify their waste in accordance with the European List of Waste (LoW codes).
- Record key information such as quantities, types of waste, destination, and type of treatment applied.
- Regularly inform national authorities through annual or semi-annual reports.
- Ensure the traceability of waste, especially in the case of hazardous or semi-liquid waste, such as cutting sludge (European Commission, 2018; Eurostat, 2022).

In countries such as Spain, Italy and other EU members, this traceability is managed through digital platforms such as eSIR, SISTRI or SIGRE. These tools allow volumes to be reported, waste to be classified and the place of disposal to be confirmed. In addition, waste reports are often integrated into Environmental Product Declarations (EPDs), such as RCP004 for natural stone, developed by ITeC and CTM (ITeC & CTM, 2021). These declarations include environmental impact indicators, such as the kilograms of waste generated per square metre of processed stone, water consumption and CO_2 emissions.

2.4 Consequences of Non-compliance

Failure to comply with legal obligations in waste management can have serious consequences, including:

- **Fines and penalties:** Violations such as improper transport of waste, illegal dumping, or incorrect labelling can result in administrative or even criminal penalties (European Commission, 2020a).
- **Environmental liability:** The Environmental Liability Directive (2004/35/EC) establishes the 'polluter pays' principle, which obliges companies to repair or compensate for any damage caused to the environment, even if it was unintentional (European Parliament & Council, 2004).
- **Suspension or withdrawal of permits:** Facilities operating under IPPC or IED authorisations may face closure if repeated non-compliance is detected.

2.5 Training Relevance for VET Learners

In order to adequately prepare vocational training students or adults who are pursuing careers in stonemasonry, stone processing or environmental management, it is essential that the legal framework is not perceived as a set of abstract rules, but rather as an integral part of everyday work activities.

Learning topic	Pedagogical Goal
Waste hierarchy and circular economy	Understand how to prioritize prevention and valorization
LoW code classification	Learn to properly identify and document different types of waste
Waste reporting forms and systems	Use real digital platforms (e.g., EPD software, national registries)
Extractive Waste Management Plans (EWMP)	Understand structure and components of waste plans required for quarries
Legal compliance case studies	Analyze real scenarios with successful and failed compliance outcomes

Integrating this legal content into practical activities—such as filling out simulated reports or using simulation platforms—not only raises awareness and participation levels but also provides skills that are directly applicable in the workplace.

3. BLOCKCHAIN APPLICATIONS: MATERIAL PASSPORTS, DIGITAL TWINS, DECENTRALIZED LEDGERS

3.1 Material Passports

A material passport is a digital record that organises key information about the composition, origin and life cycle of a product or material in a structured way. In the case of ornamental stone, this passport may include data such as the type of rock, the location of the quarry, the date of extraction, the treatment applied, the amount of waste generated and the possibilities for reuse or recycling.

This approach was promoted by the European project BAMB – Buildings As Material Banks, which laid the foundations for what we now know as Digital Product Passports (DPPs). These passports have gained momentum within the European Green Deal and the 2020 Industrial Strategy (European Commission, 2020a). Companies such as Circularise are already applying this idea in industry, using blockchain technologies to ensure that information is transparent, traceable and unalterable throughout the supply chain (Circularise, 2023).

In the natural stone sector, this technology makes it possible to track each block or batch from its origin in the quarry to its final transformation. Key events such as the volume of waste generated, the destination of leftover fragments or the chemical composition of cutting sludge can be recorded. All of this is documented and can be digitally audited, facilitating the certification of sustainable practices.

Example: A batch of marble with a digital passport may show that 70% of the waste generated during its processing was reused as aggregate for mortar. This information is valuable both for responsible buyers and for environmental certification processes.

3.2 Digital Twins

A digital twin is a virtual, accurate, real-time replica of a physical object, process, or system. When combined with blockchain technology, it becomes a powerful tool for securely and transparently monitoring critical variables in processes such as stone extraction and transformation.

For example, data such as the volume of slurry generated by each machine, energy consumption according to the type of stone, or the level of waste deposits can be automatically captured using IoT sensors. This information is directly reflected in the digital twin, allowing for constant and detailed monitoring (Suhail et al., 2021). By storing this data on blockchain, it is protected against manipulation, which is key in contexts where compliance with regulations or audits is required.

According to Liu et al. (2022), the combination of digital twins and blockchain in industry not only facilitates automated decision-making and process optimisation but also improves hazardous waste management by providing an accurate representation of the physical and digital flow of materials.

This technology is already being applied in sectors such as water treatment and cement manufacturing, where precise waste control is essential (Homaei et al., 2025).

Application in stone: A granite cutting plant can operate with a digital twin that receives real-time data on the humidity, flow rate, and chemical composition of the slurry generated. When any of these values exceed the established legal limits, the system can trigger automatic alerts or take corrective action instantly.

3.3 Decentralized Ledgers and Blockchain Networks

The technological heart that makes all these functions possible is distributed ledger technology, known as DLT. Within this group, the best known is blockchain. Platforms such as Ethereum, Hyperledger Fabric and VeChain enable the creation of networks in which different actors — quarries, cutting plants, recyclers and environmental authorities — can share information securely, without relying on a central entity to control it (Ko et al., 2022).

Thanks to this, waste-related data becomes verifiable and permanent, which helps prevent fraud in sustainability reports and improves compliance with environmental regulations. In addition, this technology allows the use of smart contracts: digital agreements that are automatically executed when certain conditions are met.

For example, imagine that a carrier delivers a batch of fragments to a recycling plant. Once the plant confirms receipt and use as raw material, a smart contract could:

- Issue a token or digital certificate to the waste generator as proof of recovery.
- Automatically notify the national waste system.
- Activate a financial bonus or tax benefit if the waste plan has been correctly fulfilled.

This type of model is already being tested in initiatives such as Circularise for Plastics and in digital product passport (DPP) projects within the textile and construction sectors (Jiang et al., 2023; Ko et al., 2022).

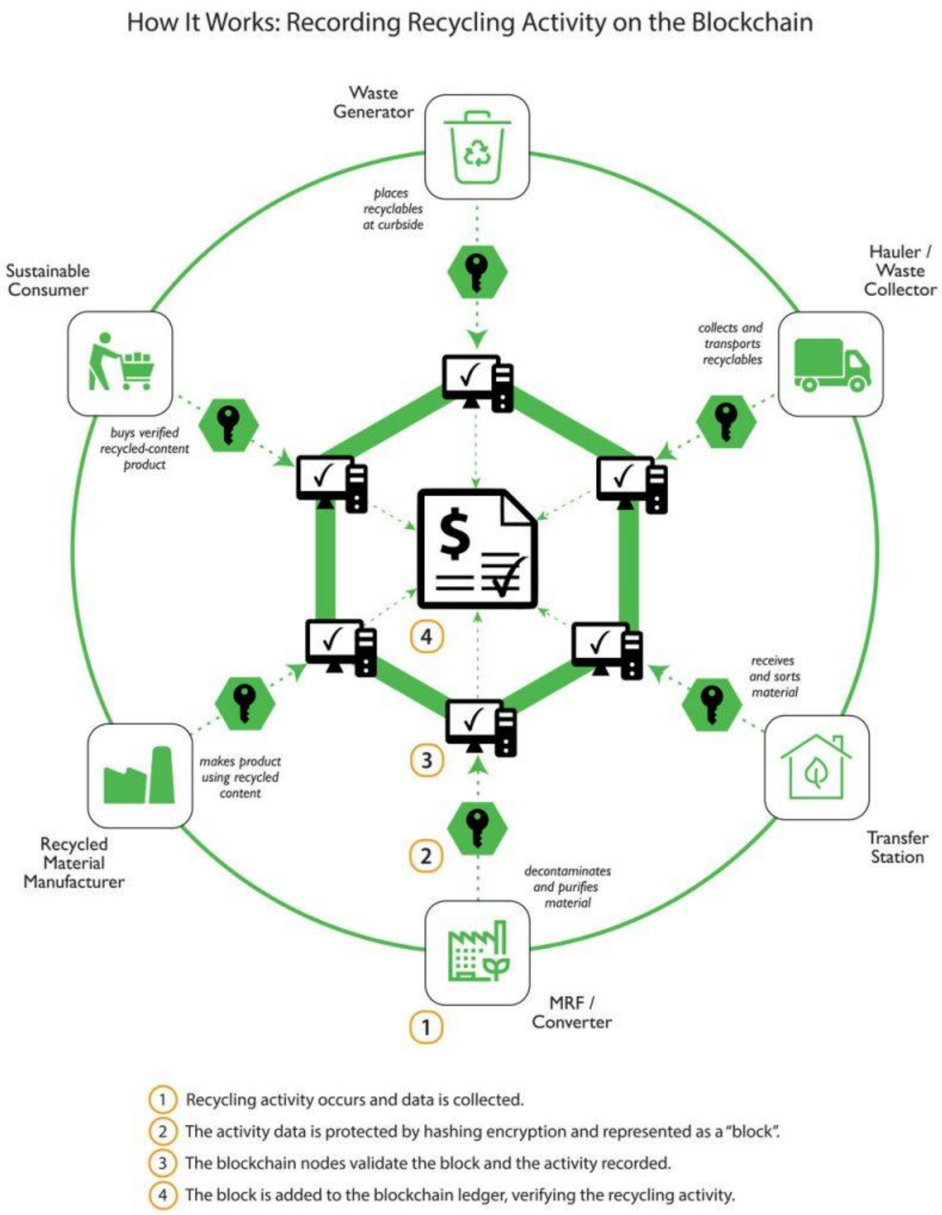

Figure 3. Recycling activity on the BlockChain. Source: https://wasteadvantagemag.com/fixing-the-recycling-supply-chain-a-blockchain-solution/?utm_source=chatgpt.com

3.4 Advantages and challenges

Advantages	**Challenges**
Total transparency and data that cannot be modified	High energy and economic costs in some public blockchains
Easy integration with sensors, digital platforms, and management systems	Compatibility issues between different blockchains and existing databases

Advantages	Challenges
Automation of certifications, reports and incentives with smart contracts	Need to comply with the GDPR and protect the confidentiality of industrial data
Useful for audits, tendering processes and circular certifications	Technological barriers and learning curve in small and medium-sized enterprises (SMEs)

3.5 Application to the stone sector: proposed workflow

1. Upon leaving the quarry, each block of stone receives a unique digital ID that identifies it throughout its entire useful life.
2. During its transformation, waste is generated and automatically recorded by sensors connected to the digital twin.
3. Every relevant action—such as cutting, slurry generation, or fragment separation—is stored in a blockchain with a timestamp.
4. If a certain level of valuation is reached or complete traceability is confirmed, the system automatically issues a digital verification.
5. All this information is integrated into a Digital Material Passport, accessible to all stakeholders: from producers to auditors to end customers.

This model not only strengthens the legal traceability of the process, but also increases the commercial value of the product and opens doors in markets where practices aligned with ESG (environmental, social and governance) criteria are valued.

4. SMART CONTRACTS FOR COMPLIANCE, REPORTING AND INCENTIVES

4.1 What is a Smart Contract and how does it work?

A smart contract is a programme that runs automatically within a blockchain network, triggering certain actions when predefined conditions are met. Unlike traditional contracts, it does not require intermediaries — either human or institutional — to enforce the agreement. This idea was first proposed by Nick Szabo in the 1990s, and today it is an essential part of platforms such as Ethereum, Hyperledger and Tezos (Szabo, 1997; Rapid Innovation, 2023).

In the field of waste management, smart contracts can help automate processes such as:

- Recording deliveries to treatment plants.
- Verifying compliance with environmental standards.
- Automatically generating environmental reports.
- Activating incentives when waste recovery targets are met.

In addition to saving time and resources, this automation improves transparency and strengthens trust among all stakeholders (Rapid Innovation, 2023).

4.2 Applications in waste management and the circular economy

Various studies and pilot projects have shown that smart contracts can revolutionise the way waste is managed, making it more efficient, transparent and secure:

In a model proposed by Bułkowska et al. (2023), smart contracts enable automatic control of the entire waste flow: from its generation to its final treatment. This includes external validations, automatic notifications to authorities and the issuance of digital certificates.

Dasaklis et al. (2020) applied this approach to e-waste management, creating a system where each stage — collection, recycling, and material recovery — is recorded in an immutable way, thus preventing fraud or illegal practices.

In the context of the circular economy, these contracts are also used to assess the environmental performance of companies. If certain key indicators are met, automatic incentives in the form of digital tokens are activated (Jiang et al., 2023).

Practical example: if a quarry manages to reuse or recycle more than 60% of its waste, a smart contract could automatically issue a 'green digital seal' that is added to the product's digital passport.

4.3 Specific use cases in the stone sector

4.3.1. Automatic compliance certification

In many regions, plants are required to demonstrate that they manage their waste in accordance with regulations. Currently, this involves inspections, manual signatures, and a large number of physical documents or PDFs.

With the use of smart contracts, this process can be automated:

- The plant receiving the waste (e.g., a marble slurry recycler) digitally validates its receipt and treatment.
- The smart contract automatically checks that the destination is authorised and that the type of waste is permitted.
- If everything is correct, a digital certificate of compliant treatment is generated and recorded on the blockchain.

This certificate can be shared directly with environmental authorities, auditors or customers, without the need for repeated reports or manual validations.

4.3.2. Incentives for environmental performance

Sustainability can also translate into automatic rewards:

- If a company reduces, for example, 20% of the volume of waste disposed of compared to the previous year, a smart contract can release a digital eco-bonus or apply a tax discount in its management system.
- These incentives can be used in green public procurement, tenders or circular economy platforms between companies.

According to França et al. (2020), this approach can even be applied at the municipal level to reward small businesses that meet demonstrable sustainability criteria.

4.3.3. Automation of legal reporting

One of the most repetitive and costly tasks in many industries is the periodic preparation of reports for environmental authorities.

With smart contracts, this process can be significantly simplified:

- Each time waste is transported, processed or disposed of, a time-stamped record is generated.
- This record is automatically sent to the corresponding regional or national system (such as eSIR in Spain or SISTRI in Italy).
- If legal requirements are not met, the system can issue a preventive alert or a non-compliance notification.

This not only reduces the margin for human error but also reinforces traceability and regulatory compliance in a transparent and real-time manner.

4.4 Benefits and challenges

4.4.1. Main advantages:

- Less bureaucracy: By automating reports, signatures, and validations, the time spent on administrative tasks is significantly reduced (Rapid Innovation, 2023).
- Total transparency: Data recorded on the blockchain cannot be modified and can be audited by any authorised party.
- Scalability: Smart contracts allow multiple actors — quarries, recyclers, authorities — to be integrated into the same trusted network.
- Automatic incentives: Rewards or benefits can be programmed according to environmental performance, transparently and without manual intervention.

4.4.2. Key challenges:

- Initial investment: Although profitable in the long term, the development and implementation of smart contracts requires an initial investment in technology and training (Bułkowska et al., 2023).
- Lack of common standards: For different platforms to work together, it is necessary to agree on compatible data structures and shared rules (Jiang et al., 2023).
- Privacy and regulation: It is essential that contracts comply with regulations such as the GDPR, especially if they handle sensitive information (Dasaklis et al., 2020).
- Resistance to change: In traditional sectors such as natural stone, especially among SMEs, there may be reluctance to adopt new digital technologies.

4.5 Teaching proposal for Vocational Education and Training (VET)

Activity	Educational objective
Simulation of a smart contract	Understand step by step how an operation (such as waste certification) is automated
Role play (generator, recycler, auditor)	Practise waste verification and the issuance of digital certificates in a simulated environment
Analysis of real tokenised cases	Identify the advantages and challenges of using digital incentives in environmental contexts
Debate on privacy and transparency	Encourage critical thinking on how to balance traceability with data protection

These activities can be easily implemented using free tools such as Remix, an online platform for simulating smart contracts in Solidity, or using visual templates that represent waste management processes.

5. INTEGRATION OF BLOCKCHAIN WITH IOT AND DATA COLLECTION TOOLS

5.1 The role of IoT in waste management

The Internet of Things (IoT) allows data from the physical world to be captured in real time thanks to distributed sensors. These sensors can measure variables such as deposit levels, humidity, volume, and the chemical composition of sludge and stone fragments. By providing a detailed and up-to-date view of waste flow, it reduces reliance on manual records, lowers logistics costs, and improves overall process efficiency (Gulyamov, 2023).

For example, the use of IoT sensors has in some cases reduced logistics costs by up to 40% and CO_2 emissions by 20-30% by optimising waste collection routes based on real-time data.

In a stone processing plant, IoT sensors can work simultaneously to:

- Measure the flow of cutting water.
- Detect the level of sedimented sludge.
- Identify the presence of fine particles.
-

This data can be sent directly to a blockchain network, ensuring its secure recording and facilitating environmental traceability.

5.2 Blockchain as the backbone of traceability

When IoT is combined with blockchain, a system is created in which digital records are immutable, auditable, and accessible to all stakeholders, without the need for intermediaries. According to Jiang et al. (2023), blockchain addresses three key needs in modern waste management: security, data integrity, and transparency.

Today, there are advanced models that integrate IoT sensors, blockchain, artificial intelligence, and life cycle analysis, enabling the development of much smarter and more sustainable management systems.

Practical example: an IoT sensor measures the volume of sludge generated in real time. When a certain value is reached, a smart contract is automatically activated, which records the event on the blockchain and verifies that the data complies with regulatory or recovery requirements.

This type of automation ensures robust traceability, reduces errors and facilitates legal compliance almost instantly.

5.3 Combined technical architecture: Edge, IoT and Blockchain

To achieve efficient and sustainable traceability in waste management, a technical architecture combining three key layers is recommended:

1. IoT sensors in machinery: these are installed directly in cutting, pumping or treatment equipment and detect critical parameters such as sludge level, waste volume or water quality.
2. Edge Computing layer: this intermediate layer is responsible for filtering, processing and validating data locally before sending it to the main network. This helps reduce latency, lower blockchain usage costs and avoid overloading the system with unnecessary data.
3. Permissioned blockchain (such as Hyperledger or IOTA): this network only records relevant events, activates smart contracts when certain conditions are met, and ensures secure and verified traceability.

This model is not only scalable, but also energy efficient, making it ideal for distributed industrial environments such as cutting plants, quarries or waste recovery centres.

5.4 Benefits and challenges of IoT + Blockchain integration

5.4.1. Key benefits:

- Frictionless automation: data generated by IoT sensors is automatically recorded on the blockchain and triggers smart contracts without the need for human intervention.
- Operational improvement: through predictive analytics, equipment downtime can be reduced, collection routes optimised, and waste recovery processes improved.
- Real-time auditing: automatic records enable immediate and reliable regulatory control, without relying on manual processes or retrospective reports.

5.4.2. Main challenges:

- High initial investment: installing sensors, setting up Edge Computing infrastructure and developing blockchain solutions involves significant upfront costs.
- Security and privacy: IoT devices can be vulnerable, and sensitive industrial data must be protected in compliance with regulations such as the GDPR.
- Interoperability: there are multiple IoT and blockchain platforms, which requires common standards so that all systems can communicate correctly (Jiang et al., 2023).

5.5 Practical application in the stone sector

This is an example of how the integration of IoT, Edge Computing, blockchain and digital twins can be applied in a concrete way in a stone processing plant:

1. IoT sensors installed in the sludge tanks measure the level and density of the accumulated material in real time.
2. This information is processed locally using Edge Computing, which verifies whether a predefined minimum volume (e.g. 5 m^3) has been reached.
3. Once validated, an event is automatically generated in the blockchain, which activates a smart contract that records the event and issues a digital certificate or token of value.
4. This data is incorporated into the digital twin of the batch, where waste metrics, treatment, percentage recovered, and final destination are integrated.
5. Finally, all this information is uploaded to the material's digital passport, facilitating access to ESG certifications, public tender processes or traceability for buyers looking for sustainable materials.

REFERENCES

Chen, Z. (2024). *Environmental alternatives for stone slurry circularity: from waste to resource* (Tesis de Máster, Politecnico di Milano). Disponible en línea: https://www.politesi.polimi.it/retrieve/4e15e145-769a-4162-9eb0-d3c3acb39830/2023_12_Chen.pdf orbi.uliege.be+3politesi.polimi.it+3unitesi.unive.it+3

European Commission. (2020a). *A new Circular Economy Action Plan: for a cleaner and more competitive Europe*. Documento completo disponible: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0098

Eurostat. (2022). *Waste statistics – Statistics explained*. Accesible en: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics

Jalalian, M. H., Bagherpour, R., & Khoshouei, M. (2021). *Wastes production in dimension stones industry: resources, factors, and solutions to reduce them*. Environmental Earth Sciences, 80. DOI: 10.1007/s12665-021-09890-2. Incluye PDF y cita en ResearchGate OUCI+9ResearchGate+9giab-online.ru+9

LIFE-ZSW (2024). *Demonstration of an innovative environmentally-friendly and economically-feasible technology for recycling ornamental stone waste*. Programa LIFE – Unión Europea. Disponible en: giab-online.ru+3OUCI+3unitesi.unive.it+3

Piumonte Study. (2021). *Sludge production in the marble industry of Verbania*. MDPI, *Environment, Development and Sustainability*, 5(1), 57. PDF accesible vía MDPI unitesi.unive.it

DAPcons. (2021). *RCP004: Piedra natural. Reglas de categoría de producto para la elaboración de DAP sectorial*. Instituto de Tecnología de la Construcción (ITeC), CTM, y colaboradores. Disponible en: https://csosteniblev4.s3.eu-west-1.amazonaws.com/documents/20210505_DAPcons_RCP004_v3.pdf

European Commission. (2018). *Guidance on the interpretation of key provisions of Directive 2008/98/EC on waste*. https://ec.europa.eu/environment/pdf/waste/framework/guidance_doc.pdf

European Commission. (2019). *Best practices in extractive waste management plans*. https://ec.europa.eu/environment/pdf/waste/mining/guidance_extractive_waste.pdf

European Commission. (2020b). *Eco-Management and Audit Scheme (EMAS)*. https://ec.europa.eu/environment/emas/index_en.htm

Eurostat. (2022). *Waste statistics – Statistics Explained*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics

European Parliament & Council. (2008). *Directive 2008/98/EC on waste (Waste Framework Directive)*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098

European Parliament & Council. (1999). *Directive 1999/31/EC on the landfill of waste*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31999L0031

European Parliament & Council. (2010). *Directive 2010/75/EU on industrial emissions*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32010L0075

European Parliament & Council. (2004). *Directive 2004/35/EC on environmental liability*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32004L0035

ITeC & CTM. (2021). *RCP004: Natural stone. Product Category Rules for Environmental Product Declarations (EPDs)*. https://csosteniblev4.s3.eu-west-1.amazonaws.com/documents/20210505_DAPcons_RCP004_v3.pdf

Circularise. (2023). *A sustainable future using blockchain for Digital Product Passports*. https://www.circularise.com/blogs/a-sustainable-future-using-blockchain-for-digital-product-passport

European Commission. (2020). *A new Circular Economy Action Plan: For a cleaner and more competitive Europe*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0098

Homaei, M., et al. (2025). *Smart Water Security with AI and Blockchain-Enhanced Digital Twins*. arXiv preprint. https://arxiv.org/abs/2504.20275

Jiang, P., et al. (2023). *Blockchain technology applications in waste management: Overview, challenges and opportunities*. Journal of Cleaner Production, 421, 138466. https://doi.org/10.1016/j.jclepro.2023.138466

Ko, R., et al. (2022). *Digital Product Passport Implementation Based on Multi-Blockchain Architecture*. Applied Sciences, 12(11), 4874. https://www.mdpi.com/2076-3417/12/11/4874

Liu, J., Yeoh, W., Qu, Y., & Gao, L. (2022). *Blockchain-based Digital Twin for Supply Chain Management: A Review*. arXiv preprint. https://arxiv.org/abs/2202.03966

Suhail, R. S., Jurdak, R., Oracevic, A., et al. (2021). *Blockchain-Based Digital Twins: Research Trends, Issues, and Challenges*. arXiv preprint. https://arxiv.org/abs/2103.11585

Bułkowska, K., Zielińska, M., & Bułkowski, M. (2023). Implementation of Blockchain Technology in Waste Management. *Energies, 16*(23), 7742. https://doi.org/10.3390/en16237742

Dasaklis, T. K., Casino, F., & Patsakis, C. (2020). A traceability and auditing framework for electronic-equipment reverse logistics based on blockchain. *arXiv preprint arXiv:2005.11556*. https://arxiv.org/abs/2005.11556

França, J., et al. (2020). Proposing the use of blockchain to improve solid waste management in small municipalities. *ResearchGate preprint*. https://www.researchgate.net/publication/336194492

Gorkhali, A., Li, L., & Shrestha, A. (2020). Blockchain-based solid waste management traceability system. *International Journal of Environmental Science & Technology, 19*, 7833–7856. https://doi.org/10.1007/s13762-020-02850-2

Jiang, P., et al. (2023). Blockchain technology applications in waste management: Overview, challenges and opportunities. *Journal of Cleaner Production, 421*, 138466. https://doi.org/10.1016/j.jclepro.2023.138466

Rapid Innovation. (2023). Smart contracts in supply chain management: benefits, use cases, and examples. https://www.rapidinnovation.io/post/smart-contracts-in-supply-chain-management-enhancing-transparency-and-efficiency

Gulyamov, S. (2023). *Intelligent waste management using IoT, blockchain technology and data analytics*. E3S Web of Conferences. https://www.e3s-conferences.org/articles/e3sconf/pdf/2024/31/e3sconf_iccsei2023_01010.pdf PMC+1taylorfrancis.com+1eprints.whiterose.ac.uk+2ResearchGate+2PMC+2e3s-conferences.org+1ResearchGate+1

Jiang, P., Zhang, L., You, S., Fan, Y. V., Tan, R. R., & Klemeš, J. J. (2023). Blockchain technology applications in waste management: overview, challenges and opportunities. *Journal of Cleaner Production, 421*, 138466. https://doi.org/10.1016/j.jclepro.2023.138466 ResearchGate

He, X., Chen, D., Zhang, N., Dai, H.-N., & Yu, K. (2022). *Integration of blockchain and edge computing in Internet of Things: a survey*. arXiv. https://arxiv.org/abs/2205.13160 arXiv

Pan, J., Wang, J., Hester, A., Alqerm, I., Liu, Y., & Zhao, Y. (2018). *EdgeChain: an Edge-IoT framework and prototype based on blockchain and smart contracts*. arXiv. https://arxiv.org/abs/1806.06185 arXiv

RockChain Course: UNIT 5. RockChain. Final practical exercise: integrative project.

"Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them."

Erasmus+

DNV

Centro Tecnológico del mármol, piedra y materiales

Transilvania University of Brasov

Contents

1. INTRODUCTION

This final unit brings together the knowledge acquired throughout the course by analysing the RockChain App, an educational game that uses blockchain technology applied to waste management in the stone industry. It presents its current functionalities, the dynamics of the game, the interface, the roles that users can assume, and some good practices taken from other related Erasmus+ program projects. The unit closes with a final assessment that helps reinforce what has been learned.

2. ROCKCHAIN PLATFORM FUNCTIONALITIES

RockChain App is an educational platform with a gamified approach, designed to help students understand how a blockchain-based economy works by simulating a market for natural stone, industrial waste and recovery processes. In this environment, participants take on the role of players who must manage limited resources, make strategic decisions and choose to collaborate or compete with other users to obtain the best possible performance.

Throughout the game, users become familiar with key concepts such as material traceability, the value of recycling, digital mining (based on proof of work) and smart contracts. The dynamics combine technical and economic aspects, recreating situations typical of the ornamental stone value chain in an interactive and realistic environment.

2.1 General navigation

The RockChain interface is designed for easy navigation using tabs located at the bottom of the screen. From there, players can access the main game modules: Market, Profile, Statistics, and Recycling.

In addition, there are other screens that are activated at specific moments in the game. For example, the waiting room before the game begins, the mining space where mathematical problems are solved, or the final screen that displays the results at the end of each round. These screens are loaded automatically thanks to the real-time event system, which uses technologies such as Firebase and WebSockets.

2.2 Game modules

LogIn: Access module that allows users to register or log in to RockChain using their email address and password. It is the entry point to the platform and guarantees individual identification for tracking games and personalised statistics.

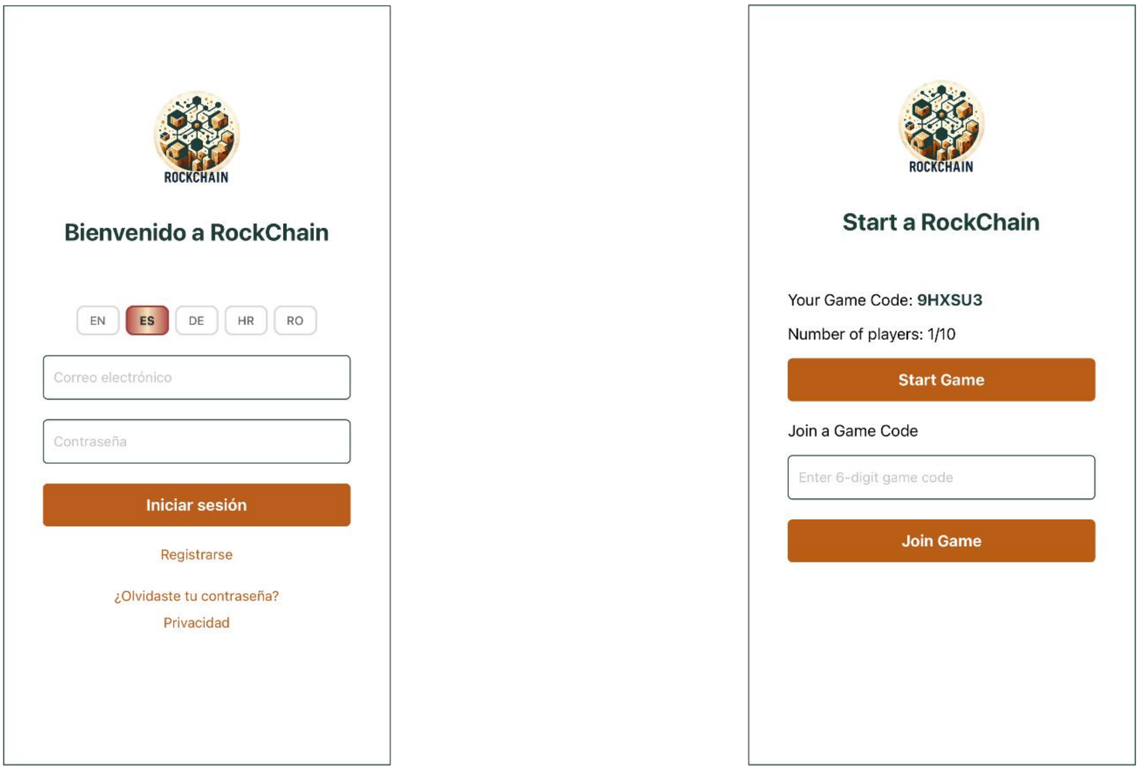

Figure 1. Login.

Waiting room: This is the first space players see when they join a game. All participants are displayed here while they wait for the moderator or 'host' to start the game.

Market: This is the heart of the game. Here, players buy and sell products related to natural stone: blocks, waste, recycled materials, among others. Prices vary, and each decision has an impact on the development of the game. Each transaction triggers an event on the blockchain and can lead to a mining phase.

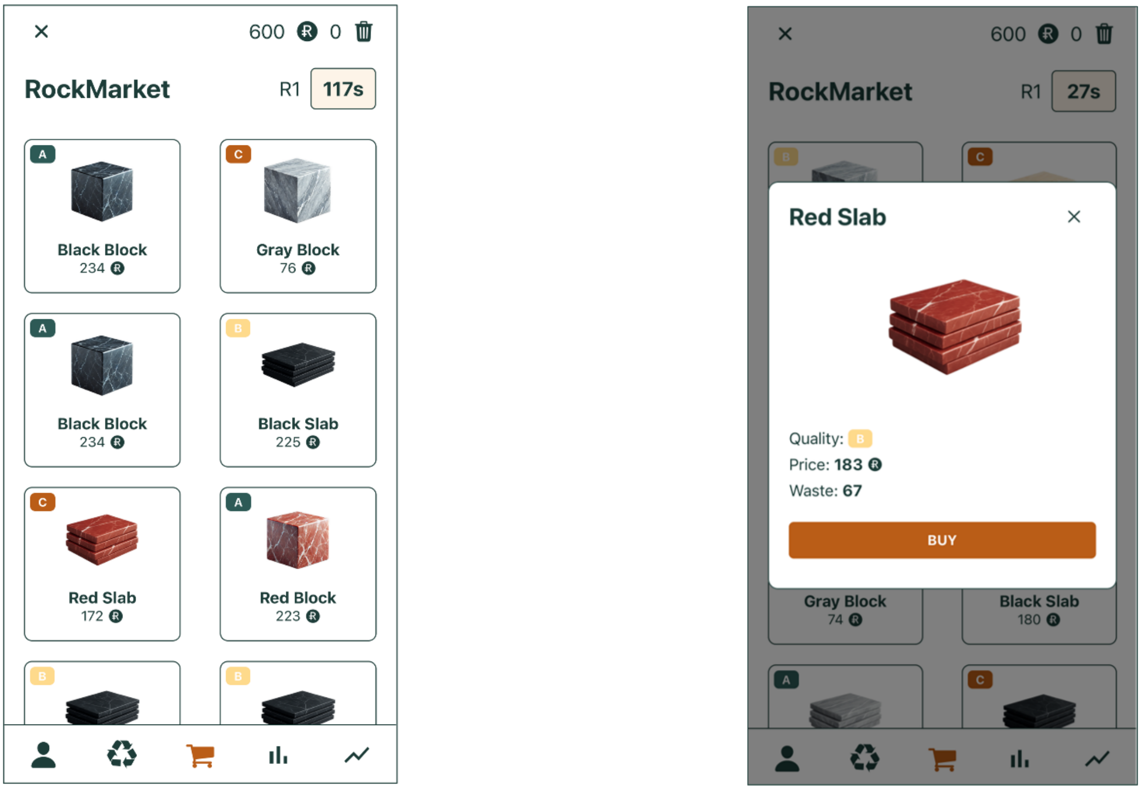

Figure 2. RockMarket area.

Mining: After certain transactions, a mathematical problem is generated that simulates a proof of work. Players compete to solve it first, and whoever succeeds receives a reward in the form of RockCoins.

Statistics: Provides an overview of player performance: ranking, accumulated resources, and operations performed. This information helps in planning subsequent decisions.

Profile: Each player has a digital inventory where they can check the products they own, mined resources, accumulated coins, and their action history.

Recycling: This module allows certain waste or by-products to be converted into new resources or RockCoins, thus promoting the circular economy within the game.

End of round: At the end of the time allocated for each round, a summary of the results is displayed: selected industry, player who successfully mined, balance evolution, and preparation for the next cycle.

2.3 User roles

All players have access to the same features during the game, with one difference: the room creator (host) has the power to start the game when everyone is ready. There are no hierarchies or additional privileges, ensuring an equitable educational experience for all participants.

The game status is managed in real time through a centralised system that updates players' devices using Firebase and socket events. This system controls aspects such as round progress, product availability, and mining results.

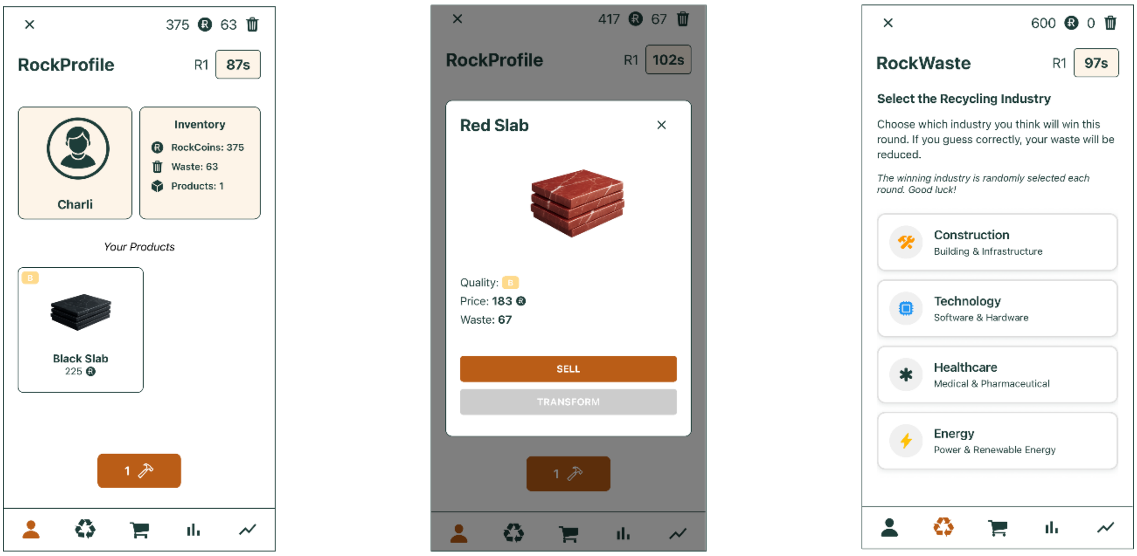

Figure 3. RockProfile.

2.4 Download and installation

RockChain is currently in the testing phase and is available for Android and iOS devices. It can also be run in development mode using Expo. The ways to access it are:

- **Expo Go:** By scanning a QR code from the Expo website, you can try out the app without having to install it completely.
- **APK (Android):** Direct installation for internal testing.
- **TestFlight (iOS):** Access by invitation, with limited availability.

Recommended technical requirements:

- Operating system: Android 8 or higher / iOS 13 or higher.
- Stable internet connection (Wi-Fi or mobile data).
- Minimum screen resolution: 720x1280 px.
- Free storage: at least 200 MB.

3. TEMPLATES AND WORKFLOWS

RockChain works as an educational simulation in rounds, combining economic decisions, problem solving and resource management. Its dynamics are cyclical but flexible, as it seeks to recreate a digital value chain involving elements of blockchain and the circular economy.

3.1 Start and preparation

The player accesses the application, registers or logs in, and joins a waiting room, where all the participants in the game are grouped together.

Once everyone is connected and ready, the room creator (host) starts the game.

During this phase, players can see who else is connected and have a timer that indicates how long until the game starts.

3.2 Gameplay by rounds

Each game consists of several rounds that follow the same structure:

- **Start of the round:** A timer visible to all players is activated. During this time, each player can freely perform actions in different modules.
- **Strategic actions:** Participants must buy, sell, transform or mine products linked to the ornamental stone sector. Each decision has a cost, an impact and possible immediate consequences:
    - Purchases and sales generate transactions that influence market logic.
    - Some transactions activate the mining phase, where players compete in real time to solve a mathematical problem. The first to do so receives RockCoins as a reward.
    - The recycling module allows low-value products to be transformed into useful resources or RockCoins, thus promoting the logic of the circular economy.

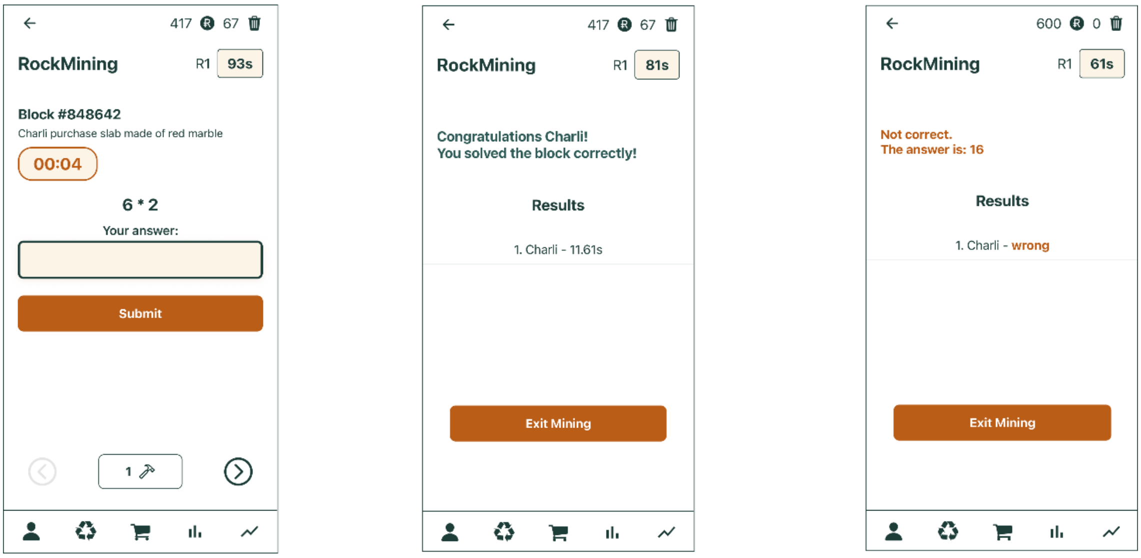

Figure 4. RockMining.

- **Real-time updates:** All actions are immediately reflected in profiles and in the statistics section, making it easy to compare strategies and balances. The socket system maintains automatic synchronization between all participants.
- **End of round:** When the timer reaches zero, operations are blocked, and players are automatically taken to the round closing screen.

3.3 Closing and evaluation of each round

The final screen of each round shows the results:

- The randomly selected industry (consumer of recycled materials).
- The player who solved the mining challenge (if any).
- Each participant's updated balance: accumulated products, RockCoins, and efficiency.

Before starting the next round, each player must confirm that they are ready. When everyone has done so, a new countdown begins and the cycle restarts.

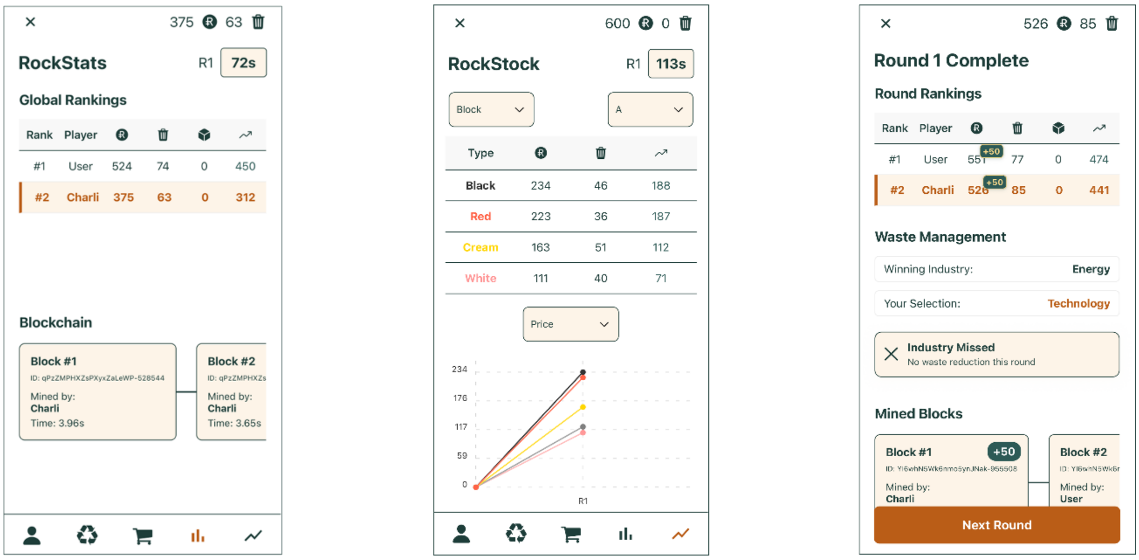

Figure 5. RockStarts, RockStock and Round completed.

Generally, a game consists of 3 rounds. At the end, an overall result is presented that reflects each player's performance and the effectiveness of their strategic decisions.

3.4 Educational principles applied to Flow

RockChain's dynamics were designed with clear pedagogical objectives, aligned with experience-based learning, the circular economy and digital literacy. More than just a gaming environment, it is intended as an educational tool that brings students closer to complex concepts related to sustainability, traceability and emerging technologies in a practical and accessible way.

The main principles applied are as follows:

- **Traceability:** Every action—purchasing, selling, recycling, or problem solving—is immediately recorded in the player's profile. This allows players to observe the consequences of their decisions in real time, understand how a blockchain is built, and appreciate the importance of transparency in production processes. It is an effective way to experience how a blockchain works without the need for advanced technical knowledge.

- **Individual and collective responsibility:** Although each player manages their own inventory and resources, their decisions have an impact on the shared environment: they modify market prices, affect the availability of materials and influence subsequent rounds. This interdependence helps players understand the logic of complex systems and reinforces the need to balance personal gain with common sustainability.

- **Applied gamification:** The round-based structure, RockCoin rewards, competitive mining mechanics, and real-time rankings make the experience motivating. These elements encourage active participation, concentration, and commitment from students. In addition, immediate feedback facilitates both understanding and retention of content.

- **Improvement cycle:** Each round functions as a new opportunity. Players can reflect on their previous decisions, adjust their strategy, and improve their performance. This iterative approach enhances skills such as critical thinking, self-assessment, and strategic planning, all of which are essential in vocational training (VET/ADU) contexts.

Together, these principles make RockChain an active learning platform that allows for the cross-cutting development of digital, environmental, and social skills.

4. CASE STUDY STRUCTURE

RockChain allows you to recreate a complete waste management game applied to the ornamental stone industry. Players take on the role of economic agents in a blockchain-based environment, where they must make strategic decisions and experiment with market dynamics and sustainability.

To show how it works, a typical case study and its components are described below.

4.1 System actors

Players: active participants who manage resources, buy and sell products, engage in mining, and seek to maximise their economic and environmental performance.

Game system: logical engine that coordinates rounds, updates prices, controls timers and validates actions in real time using sockets and a database.

Winning industry: at the end of each round, a consumer sector for recycled materials is selected at random. Players who have bet on that industry obtain additional profits.

4.2 Digital assets and game products

The resources available in RockChain include:

- Stone blocks (raw or processed)
- Industrial waste
- RockCoins (internal virtual currency)
- Digital passports or Blocks in the blockchain (associated with purchased products)

Each asset can be stored, transformed or exchanged. Its value depends both on the actions of the players and on the industry selected at the end of each round.

4.3 Complete flow of a game

Waiting room: players log in, are shown as connected, and the game is prepared.

Round 1: the counter is activated. Participants buy, sell, transform, or recycle. Each action generates a block in the game's blockchain. Some actions can trigger a mining challenge.

Mining: a 'proof of work' type mathematical problem is posed. The first to solve it gets RockCoins.

End of round: an overall summary is presented. A recycling industry is randomly selected, inventories are updated, and profits are calculated.

Ready-check: each player confirms they are ready to continue.

Rounds 2 and 3: The cycle repeats with new strategic opportunities.

End of game: The final rankings are displayed. The winner is the player with the highest overall score, considering efficiency, recycling, and accumulated RockCoins.

4.4 Checkpoints and compliance

Checkpoints function as milestones that ensure the orderly progress of the game and compliance with the rules:

- Start of round (with shared timer)
- Mining activation (mathematical challenge)
- Selection of winning industry (from backend)
- Inventory evaluation (individual balance + industry bonus)
- Confirmation of progression to the next round (readiness check)

All actions are recorded in Firestore and through socket events, allowing the game to be reconstructed, decisions to be audited, and the traceability of the system to be reinforced.

4.5 Final reporting and visualisation

At the end of the game, a visual report is generated that includes:

- Mining winner in each round
- Industry selected per round
- Final inventories of all players
- Accumulated RockCoins
- Player with the highest overall efficiency

This report can be used to stimulate classroom discussions, reflect on the strategies applied, and evaluate the skills acquired by the students.

5. REPORTING AND DOCUMENTATION BEST PRACTICES

5.1 Blockchain for the Environment: Open Interdisciplinary Education on Generating Disruptive Change through Impactful DLT Applications

Background
Environmental sustainability is identified as one of the most urgent global challenges, strongly linked to health, prosperity, and societal resilience. Distributed Ledger Technology (DLT) offers transparency, accountability, and immutability, making it a promising tool for driving behavioural change. However, its potential in non-financial domains, particularly environmental sustainability, has been underexplored, and higher education curricula rarely integrate it with interdisciplinary fields.

Objectives
The project aims to strengthen European higher education by integrating DLT with Environmental Engineering, Design Thinking, and Behavioral Psychology/Economics at the Master's level. Its goal is to develop curricula and digital resources that cultivate a "green" and "decentralised" mindset, enabling students and professionals to design decentralized applications that address environmental challenges strategically.

Activities
BC4ECO implements transnational project meetings, summer schools, and teacher training workshops to co-create and validate its pedagogical framework. It also organizes multiplier events at European conferences to engage stakeholders and promote dissemination and adoption of its results across universities.

Impact
The project establishes a benchmark for interdisciplinary education on DLT applied to environmental sustainability. By producing an innovative curriculum, MOOCs, and open resources, it equips future professionals with the skills to design impactful applications, closes existing skills gaps in the labour market, and fosters a sustainability-oriented digital ecosystem.

Project website: https://bc4eco.eu/

Figure 6. BC4ECO project logo

5.2 Innovative training approach in the technology-assisted environment for water management

Background

Climate change affects water availability and quality in energy, infrastructure, human health, agriculture, and ecosystems. Staff credentials and attracting young workers remain key issues in Europe. To attract highly qualified workers, learning initiatives must make water management in associated sectors appealing and translate academic knowledge and high-level basic and transversal competences into practical skills.

HE prioritises the "Knowledge Triangle" through innovation, entrepreneurship, and university-business collaboration. This is especially true for traditional sectors like environmental-related ones, where changes in education and training are needed to prepare the future workforce for the new demands created by climate change-related economic growth (e.g., water sources, tourism impact).

However, European Security and Water Sources are vital drivers of sustainable prosperity and contribute to Europe's economic health, competitiveness, creativity, innovation, employment, and growth. European staff credentials and young unemployment remain vital. To attract highly qualified workers, training must translate academic knowledge and high-level basic and transversal abilities into relevant and applicable skills.

Objectives

Paradox saw the creation of a course by 5 institutions, 3 SMES, and 1 Chamber of Commerce organisation, all of which promote educational activities in the field in different ways. Each participant entity, its personnel, students, and community are addressed by this project. From this fundamental goal, numerous specific targets were set:

1. Capacity Building in the sector: Promoting ACTIVE COOPERATION and partnership between actors from the knowledge triangle: HE institutions (BUCKS, IHU, UPM, UTB,

UNIPA), industry (EVM, EYEBB, UMOU), Chamber of Commerce (ACIF), and local/Regional Bodies to impact environmental responsibility, modernization, and internationalisation of HE.
2. Develop FLEXIBLE LEARNING PATHWAYS to teach and recognise HE students' most significant skills, such as internationalisation and digital learning. This new pathway were buld on prior learning and aimed to improve sector-specific, high-level basic and transversal competences and skills, with a focus on management, entrepreneurship, languages, and leadership, as well as their contribution to a cohesive society, particularly through increased learning and labour mobility and to
3. Promoting collaboration and mobility activities, offering more possibilities for students to obtain all the specialised and transversal skills needed, and involve them, partners' employees, and stakeholders in creating the outputs and assuring their relevance.

Implementation
Paradox main activities included the following:
-Comparative study and evidence-gathering investigations of real-life instances to determine the skills and competences needed in European Environmental investigations.
- Joint modular training programme with many learning modes (supported by Industry 4.0 and Blockchain certification).
- Develop educational materials, methodologies, and tools.
- Networking and capacity-building.
The project ended with 6 Multiplier Events and a conference.

Results
As a Strategic Partnership, Paradox produced a Study Report on current skills needs in European environmental studies, a Joint Training Curriculum, learning content, and an e-Learning platform that is freely available.
PARADOX modernised schooling and boosted traditional industry chances. It tought, evaluated, and recognised environmental abilities for participants. PARADOX also included entrepreneurship, foreign languages, and digital skills elements as outputs.
HE students, staff, and everyone involved in Paradox had the chance to develop their initiative, entrepreneurship, foreign language skills, and employability in an industrial sector that drives many European regions.

Project website: https://paradoxproject.eu/

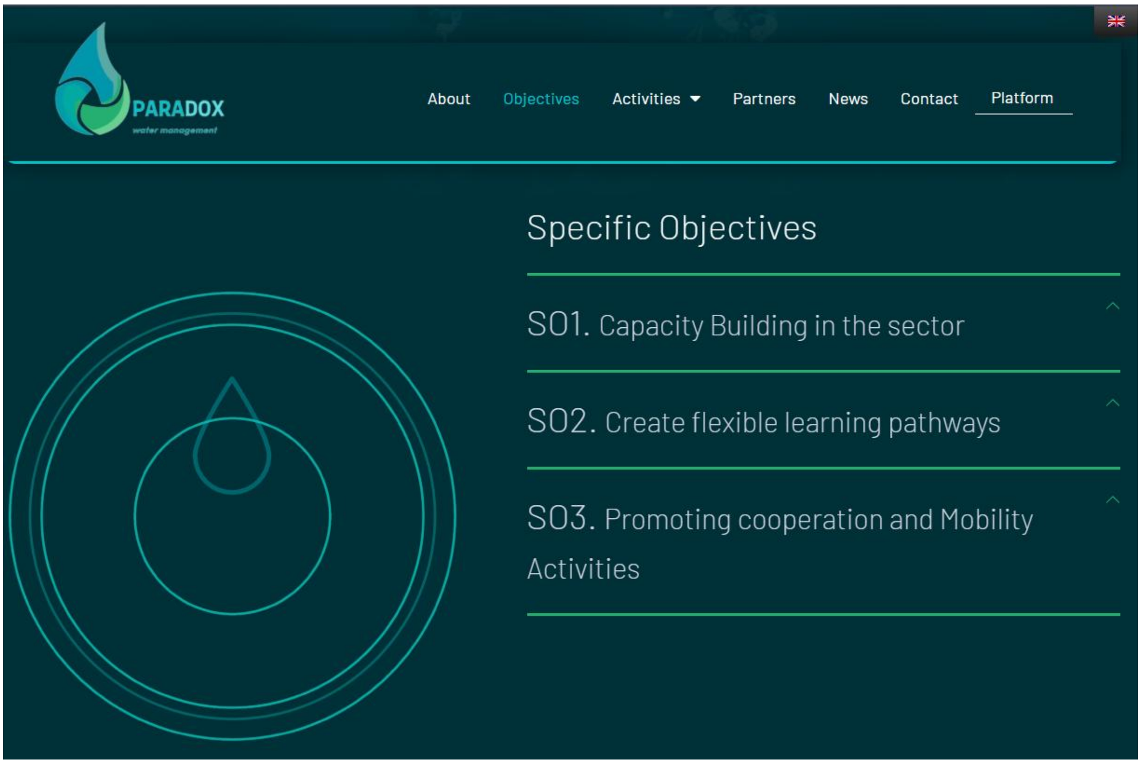

Figure 7. Paradox project website. Specific Objectives

5.3 Circular Economy Our Sustainable Future

Objectives

The "Circular Economy: Our Sustainable Future (C.E.O. for Future)" ongoing project aims to empower youth and youth workers by equipping them with entrepreneurial skills, digital tools, and policy advocacy strategies in the circular economy. It fosters sustainability-driven innovation, enhances youth employability in green industries, and promotes waste reduction, resource efficiency, and cross-sector collaboration at local and European levels.

Activities

The project will implement three key activities, each led by a partner:

Circular Economy Youth Innovation Lab – Hands-on training, hackathons, and startup incubation.

Green Policy & Community Engagement – Policy advocacy, stakeholder roundtables, and public awareness campaigns.

Digital Solutions for Circular Economy – Training in AI, blockchain, and sustainability tech solutions.

Each activity includes an 8-month cycle and a transnational mobility for 12 participants.

Impact
150+ youth and youth workers trained in circular economy and digital sustainability.
5+ youth-led circular startups launched, driving eco-entrepreneurship.
3 policy recommendations submitted to local authorities for sustainability adoption.
Circular Economy Policy Toolkit & Online Hub developed, ensuring long-term impact.
500+ community members engaged in awareness campaigns, fostering sustainable behaviors and policy change.

Project website: https://ceosforfuture.at/

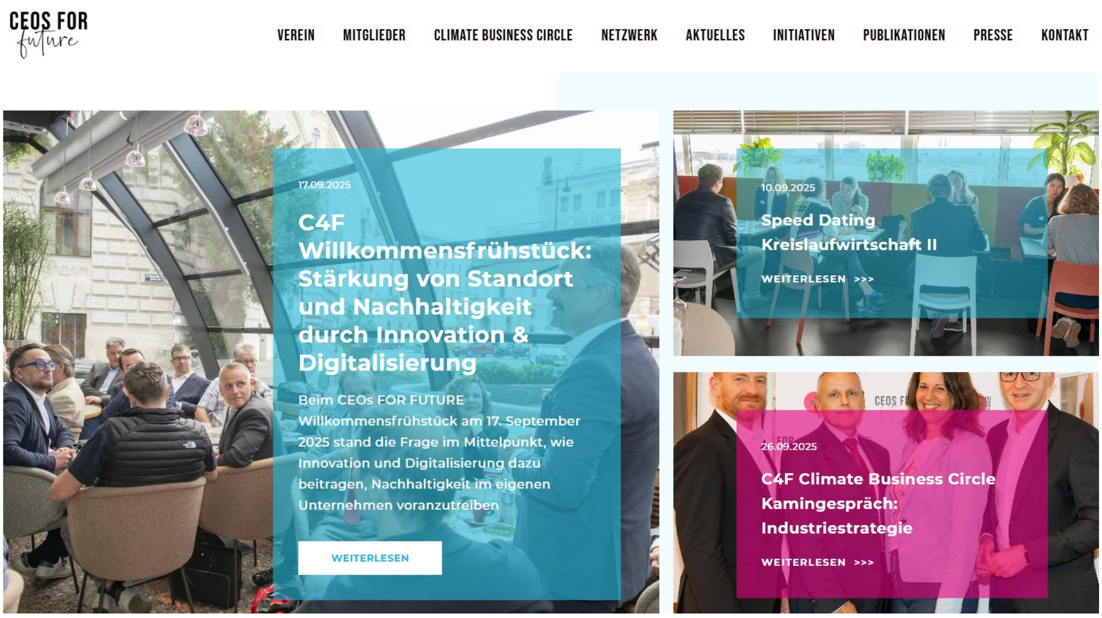

Figure 8. C.E.O. for Future project website

5.4 AGRITECH - Alliance for Innovative Learning Environment in Advanced Agriculture through Technology and Management

Background
The AGRITECH project addresses the urgent need to modernise agricultural education and training to meet sustainability and digitalisation challenges. Agriculture, as a traditional sector, is increasingly shaped by climate change, environmental pressures, and the rise of disruptive technologies. By integrating Deep Tech domains such as artificial intelligence, blockchain, quantum computing, and immersive digital tools, AGRITECH seeks to close skills gaps and prepare professionals capable of driving sustainable innovation in European agriculture.

Objectives

The project aims to transform agricultural education by creating an interdisciplinary learning ecosystem that combines technical and non-technical competences. Its main objective is to prepare a new generation of "AgriTech Managers" capable of applying advanced technologies to sustainable farming. AGRITECH also promotes creativity, entrepreneurship, and co-creation through incubators embedded in educational institutions, while embedding corporate social responsibility and sustainable development principles in training programmes.

Activities

AGRITECH develops multidisciplinary learning environments where students engage in real-world projects in collaboration with industry and research partners. New teaching methods and assessment tools are being designed, using technologies such as gamification, virtual and augmented reality, and adaptive learning. Incubation initiatives support student-led innovations, while collaborative projects foster partnerships across agriculture, technology, and education.

Impact

The project will provide innovative curricula, digital resources, and training frameworks that integrate blockchain and other emerging technologies into agriculture. It is expected to enhance the employability of learners, strengthen Europe's innovation capacity, and create a benchmark for sustainable and technology-driven agricultural education. By merging digitalisation with environmental responsibility, AGRITECH illustrates how deep tech can modernise a traditional sector, in parallel to RockChain's approach of applying blockchain and digital tools to the mining and ornamental rock industry.

Project website: https://agritech-project.eu/

Figure 9. AGRITECH project logo

5.5 Innovative training based on Blockchain technology applied to waste management

Background

It is well known that the implementation of sustainable waste management practices in the framework of circular economy is more than imperative nowadays. In the era of Industry 4.0, technological advancements could serve as mechanisms for supporting more efficient waste management practices. Blockchain could be one of these technologies that could benefit both the society and the environment. The blockchain technology was born to support and make work an electronic payment system, but nowadays, any sector can find advantages if it applies this technology properly It is a virtual distributed; usually decentralised; database, cryptographically protected and organised in linked blocks of transactions, the main advantage of which is that it cannot be modified. In the sense of immutability, blockchain can provide secure and reliable information that can be publicly accessible enabling transparency and thus building trust.

In the Municipal Waste Management (MWM) sector Blockchain could be a key factor in making trust the main enabler of circular waste management, which again makes MWM Organisations the trust broker of a waste economy.

Objectives

BlockWASTE project wishes to address the interoperability between waste management and blockchain technology, in order to promote circular economy in municipal solid waste (MSW) management by training of students and professionals from the sectors involved.

For this purpose, the objectives of this project are, as follows:

- To investigate good management practices of MSW in various European cities, so as to reintroduce waste into the value chain, promoting the idea of Intelligent Circular Cities.

- To identify the benefits of the Blockchain Technology within the MSW management process.

- To create a study plan that allows for the training of teachers and professionals in the fields of Waste Management, Circular Economy and Blockchain Technology.

- To develop an interactive tool based on Blockchain Technology, so as to make the MSW management process more visible and transparent in order to promote more circular forms of waste management.

In this direction, the main target-groups of the project are:

- Enterprises and SMEs, IT professionals, urbanisms and waste management professionals.

- Universities (professors, students and researchers).

- Public bodies.

Implementation

The main activities implemented are:

- Comparative study of a) MSW management regulations in partners' countries and EU and b) information technologies applied to MSW management at international level

- Development of 3 handbooks of Circular Economy strategies applied to Municipal Waste Management using Blockchain technologies

- Comparative study in the participating countries of a) HEI curricula on Blockchain technology and b) of HEI curricula on MSW management

- Production of a MSW management curriculum using blockchain technology

- Production of a database with information about the MSW generation and treatment in the European countries

- Development of an Interactive e-learning tool which incorporated Blockchain and MSW management modules

- Development of Open Educational Resource Platform including a Collaborative Platform

- Implementation of 3 training pilot courses

- Project management activities (e.g. monitoring, controlling and managing the project, quality assurance, etc.)

- Dissemination activities (i.e. organisation of 3 multiplier events, website development, posts in project's social media and in partners' websites, articles on e-journals, presentations on conferences, cross-links with other projects, etc.)

Results

The following 4 Intellectual Outputs are:

Learning materials in the interdisciplinary area of Blockchain-MSW management. Three (3) separate handbooks aiming to train students and professionals from the sectors involved, in the Blockchain interface and MSW management, have been developed.

European common curriculum on MSW management applying Blockchain technology. The curriculum addresses the need for skills that help transform mostly 'linear' Waste Management into Circular Economy processes. On the technical and technological side, the curriculum features on innovative tools and processes that help municipal and private waste management organizations deal with new economic challenges. The instrumental focal points in this are Blockchain and Distributed Ledger technologies.

E-Learning tool for MSW management based on Blockchain, in the light of circular economy. Two different modules have been developed.

Open Educational Resource (OER) Platform. The OER contains a Collaborative Platform based on previous Erasmus+ projects in related fields, as well as all the supporting material for the implementation of the produced BlockWASTE Course. The training materials are open to any user.

Project website: https://blockwasteproject.eu/

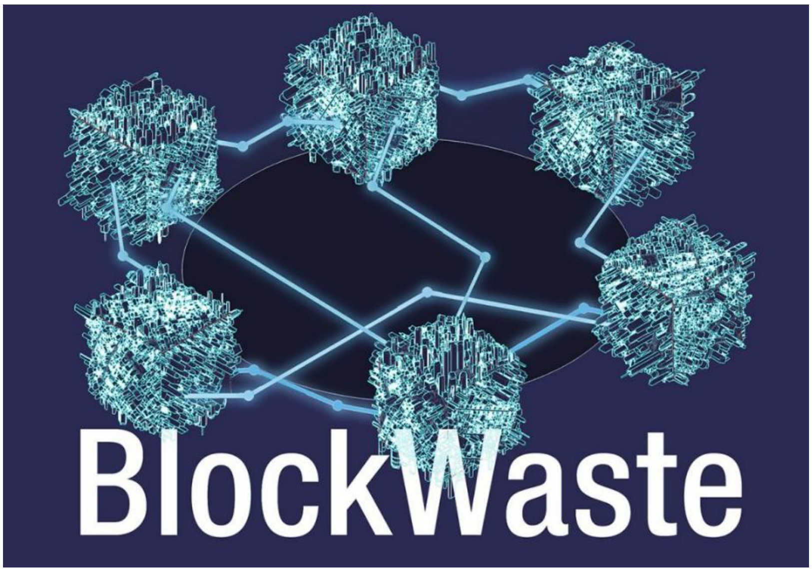

Figure 10. BlockWaste project logo

5.6 Developing a European learning outcome-oriented modular VET programme and educational resources on Blockchain to address technical, non-technical and cross-discipline (horizontal) skills requirements.

Objectives

Innovative teaching materials will be developed in the field of Blockchain, in order to contribute to the problem of incompatibility with the workforce, which is one of the biggest problems of VET. The content of the training material will be developed in the concept of climate change, carbon footprint, green EU and ICT gender equality. With our project, it is expected that qualified students will be trained in the Blockchain, and a positive contribution to the workforce with the certificates.

Activities

Our project is a project that aims to develop educational materials that support innovation and digital transformation in vocational education. To achieve these goals, 5 WPs have been prepared:

WP1- Project Management

WP2- Blockchain Framework and Modular VET Program

WP3- Assessment Platform (with AI)

WP4-Gamification-based e-learning platform

WP5- Meetings and Conferences

Impact

The expected project results are as follows.

1- Tangible Results

WP2-Blockchain Framework and Modular VET Program

WP3-Assessment Platform (With AI)

WP4-Gamification-based e-learning platform

2- Intangible Results

Increased skill and interest in the blockchain space

Contribution to the digital transformation of society in particular VET

Contribution to the adaptation of VET to the workforce

Contribution of VET to updating the curriculum according to the innovations brought by industry 4.0

Project website: https://bch4vet.eu/

BCH4VET

Developing a European learning outcome-oriented modular VET programme and educational resources on Blockchain to address technical, non-technical and cross-discipline (horizontal) skills requirements

Figure 11. BCH4VET project logo

5.7 Serious Games for Natural Resource Management

Background

The NATURE project was initiated in response to the challenges identified by the project partner group in the area of education for natural resource management. Addressing the lack of up-to-date knowledge and promoting understanding of environmental issues in business projects is fundamental to sustainable resource management. The project is a response to the need to raise awareness of the need to mitigate climate change, preserve the natural environment and the quality of life of present and future generations. Educational initiatives that prepare young professionals to become responsible, active adults in environmental sustainability in all aspects of life in industry and communities are an important part of the process. Teaching such skills ensures that students and young professionals remain relevant in their fields and act responsibly in their communities.

Objectives

The aim of the project was to provide students and teachers at universities with digital technologies and methods that contribute to the quality of education in the field of natural resource management. To achieve the impact of the project, important steps of the project were the definition of a common framework for the development of a game-based learning methodology for environmental education through exploration, collaboration and experimentation, the development of a serious game that can be used in the study process of environmental management, and the involvement of students in scenarios related to the responsible use of natural resources inspired by real life. Another important goal that led to the successful implementation of the project concept and tangible results was the provision of supporting content for teachers in the form of learning activities, videos and a reference manual that facilitates the integration of the project results into teaching practice.

Implementation

To achieve the project outcomes, the consortium developed and implemented a series of activities: a multinational research to identify and map the existing situation in natural resources management in project countries and in European space, the analysis and comparison of "Environmental Education" experiences in all partner countries in relation to digital technologies and methods that contribute to the quality of education in the field of natural resource management; the analysis of current trends in the use of games in environmental education, which led to the definition of a common framework for the development of a game-based learning methodology for natural resources management .

The educational technology team defined the learning scenarios and learning design and technology team developed NATURE serious game for students that promotes learning by doing through experimentation in the context of digital learning game. In the final phase of the project the NATURE learning intervention was validated in practice through piloting activities with higher education students in in Latvia, Greece, Portugal, Spain, Estonia and Italy. These evaluation activities in diverse academic, cultural, and economic environments ensured the European relevance of results. For project results dissemination and target group involvement in further use of project results multiplier events were organized in all project countries.

Results

The consortium implemented the project's action plan and achieved the following final results.

- The report 'An experiential, methodological learning framework for building awareness, knowledge and skills on responsible natural resources management'. The framework is based on an

analysis of stakeholder groups that stand to gain directly or indirectly from project activities on environmental education' and can be used as a reference tool for teachers who want to update their curricula based on the report's findings.

- A NATURE digital learning game and educational activities (learning scenarios and maps inspired by real-world challenges) on responsible natural resources management training, consisting of a set of deliverables, such as 3D learning scenarios, encyclopaedia, training videos

- Instructor support content in form of learning sheets for educators facilitating the adoption the proposed experiential learning design for environmental education and reference material supporting educators in the

use of the NATURE learning game and inspiring them for creating their own learning activities.

Project website: http://www.projectnature.eu/

Figure 12. Testing of NATURE serious game and project logo

5.8 Development of a serious game for digital learning in agroecology in Europe

European agriculture faces many challenges, including producing food and non-food products in sufficient quantity and quality and creating added value for farmers and actors in the food chain, while reducing agriculture's impact on the environment. Agroecology, defined as "the study of the interactions between plants, animals, humans and the environment within agricultural systems", is considered a highly relevant option for reorienting European agriculture to meet these major challenges.

However, the education provided in European universities is not yet fully adapted to train current and future agricultural professionals in agroecology. In particular, multidisciplinary approaches are not well developed in existing curricula. Moreover, current teaching methods often lack the interactive and digital dimensions that are promising learning methods. Innovative tools are therefore urgently needed to help university teachers provide high quality and attractive multidisciplinary training on agroecology to agricultural students and professionals.

The SEGAE project therefore aims to facilitate a multidisciplinary and systemic understanding of agroecology for secondary and higher education students and agricultural professionals through the development of a digital training tool. To achieve this objective, we have brought together a consortium of six European universities: University of Liège (BE), Agrocampus Ouest (FR), Groupe ESA (FR), Oniris (FR), Agricultural University of Krakow (PL) and University of Bologna (IT).

This tool takes the form of a serious game, i.e. a computer simulation game that helps players to understand in concrete terms how to implement agroecology on a farm. In concrete terms, the player manages a virtual farm combining crops and dairy cattle breeding, where she/he can implement and evaluate the impacts of agricultural practices on indicators related to the environmental, economic and social sustainability of her/his farm. She/He can make her/his choices on aspects as varied as the choice of cattle breed, animal feed ration, choice of crops, tillage method, etc. And see directly and over time the impact of her/his choices on the various indicators. Four European farm types are proposed by default: French, Italian, Belgian and Polish.

The game is aimed at teachers at universities and agricultural schools, as well as agricultural advisers in continuing education. Several pedagogical objectives can be achieved with the game: understanding the effects of different agroecological practices, global analysis of the farm, management of agroecological transitions. In addition, a scenario editor allows teachers to develop their own tailor-made pedagogical scenarios, thus meeting different learning objectives and reaching different audiences.

The game is accompanied by video tutorials and a pedagogical platform that includes a teaching guide for teachers, turnkey exercise sheets, as well as lessons on the different dimensions of agroecology addressed in the game. The game, the tutorial and the teaching tools are freely available in 6 languages (English, Spanish, French, Italian, Dutch, Polish).

In the framework of the project, more than 800 students have used the game. A training session involving 51 students demonstrated the educational interest of the game and resulted in a scientific publication (Jouan et al., 2020). Nearly 700 teachers, researchers and higher and technical education staff also received information or training on the game. Finally, more than 4,800 people have used the game since it went online.

Project pursuits that this serious game will help train high school and university students as well as agricultural professionals to contribute to the agroecological transition of European agriculture.

Project website: https://www.segae.org/

Figure 13. Project logo for Development of a serious game for digital learning in agroecology in Europe.

REFERENCES

Erasmus+ (2017). SEGAE – Development of a serious game for digital learning in agroecology in Europe (Project 2017-1-FR01-KA203-037254). Erasmus+ Project Results Platform. European Commission. Retrieved October 3, 2025, from https://erasmus-plus.ec.europa.eu/projects/search/details/2017-1-FR01-KA203-037254

Erasmus+ (2020). BlockWASTE – Innovative training based on Blockchain technology applied to waste management (Project 2020-1-EL01-KA203-079154). Erasmus+ Project Results Platform. European Commission. Retrieved October 3, 2025, from https://erasmus-plus.ec.europa.eu/projects/search/details/2020-1-EL01-KA203-079154

Erasmus+ (2020). Innovative training approach in the technology-assisted environment for water management (Project 2020-1-UK01-KA203-078871). Erasmus+ Project Results Platform. European Commission. Retrieved October 3, 2025, from https://erasmus-plus.ec.europa.eu/projects/search/details/2020-1-UK01-KA203-078871

Erasmus+ (2021). Blockchain for the Environment: Open Interdisciplinary Education on Generating Disruptive Change through Impactful DLT Applications (Project 2021-1-DK01-KA220-HED-000027608). Erasmus+ Project Results Platform. European Commission. Retrieved October 3, 2025, from https://erasmus-plus.ec.europa.eu/projects/search/details/2021-1-DK01-KA220-HED-000027608

Erasmus+ (2021). Serious Games for Natural Resource Management (Project 2021-1-LV01-KA220-HED-000032033). Erasmus+ Project Results Platform. European

Commission. Retrieved October 3, 2025, from https://erasmus-plus.ec.europa.eu/projects/search/details/2021-1-LV01-KA220-HED-000032033

Erasmus+ (2022). Developing a European learning outcome-oriented modular VET programme and educational resources on Blockchain to address technical, non-technical and cross-discipline (horizontal) skills requirements (Project 2022-1-NL01-KA220-VET-000087180). Erasmus+ Project Results Platform. European Commission. Retrieved October 3, 2025, from https://erasmus-plus.ec.europa.eu/projects/search/details/2022-1-NL01-KA220-VET-000087180

Erasmus+ (2024). AGRITECH – Alliance for Innovative Learning Environment in Advanced Agriculture through Technology and Management (Project 101187399). Erasmus+ Project Results Platform. European Commission. Retrieved October 3, 2025, from https://erasmus-plus.ec.europa.eu/projects/search/details/101187399

Erasmus+ (2025). Circular Economy: Our Sustainable Future (Project 2025-1-DE04-KA210-YOU-000358253). Erasmus+ Project Results Platform. European Commission. Retrieved October 3, 2025, from https://erasmus-plus.ec.europa.eu/projects/search/details/2025-1-DE04-KA210-YOU-000358253