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The "New" Materiality of Reconstruction: On-Site Automated Recycling of Rubble Aggregates for Rebuilding Earthquake-Stricken Villages

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Abstract

Post-disaster reconstruction remains largely excluded from circular-economy approaches. This gap is particularly evident in earthquake-affected inner territories, where reconstruction is constrained by severe logistical challenges—especially in relation to rubble management—and where debris is often composed of materials closely tied to local building cultures and community identities. In these contexts, rebuilding still predominantly follows linear, emergency-driven models that treat rubble primarily as waste. This study introduces Rubble as a Material Bank (RMB), a digital–material framework that reconceptualises earthquake rubble as a traceable and programmable resource for circular reconstruction. RMB defines a rubble-to-component chain that integrates material characterisation, data-driven management, robotic fabrication, and reversible architectural design. Selected downstream segments of this chain are experimentally validated through the TRAP project, developed within the European TARGET-X programme. The experimentation focuses on extrusion-based fabrication of dry-assembled wall components using rubble-derived aggregates. The results indicate that digitally governed workflows can enable material reuse, while also revealing technical and regulatory constraints that currently limit large-scale implementation.

Keywords: post-disaster reconstruction; circular construction process; rubble reuse; digital materiality; material bank; digital fabrication workflow

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1. Introduction: (Re)Build It Circular

Over the past decade, circularity has emerged as a central paradigm of sustainability in the construction sector, increasingly informing research and practice in architectural design and construction through a different approach to material use and a renewed focus on building life cycles. While these principles have found a clear field of application in new construction through strategies such as design for disassembly and adaptability [1], material passports [2], digital twin-based traceability systems [3], and modular prefabrication with reversible connections [4], their implementation in refurbishment and regeneration remains comparatively limited.

This limitation is particularly evident in post-disaster contexts, where reconstruction processes function as full-fledged forms of urban transformation with significant environmental and territorial impacts. Whether triggered by natural disasters or human-induced events, such processes usually generate large quantities of construction and demolition waste in the form of rubble and debris. Managing this material requires extensive, time-critical interventions, as rubble accumulation represents both a major obstacle to the initiation of reconstruction activities and a significant environmental burden in terms of storage, transport, and disposal. These challenges are further exacerbated when large volumes of debris are produced as a result of high-magnitude events, due to the structural vulnerability of the existing building stock, or in geographically constrained areas where limited accessibility makes rubble handling and transportation especially challenging. Despite the persistence of this critical condition, post-disaster reconstruction largely remains outside the scope of circularity-oriented approaches, continuing to rely on linear, emergency-driven models that limit the integration of circular principles [5].

Such limitations are primarily rooted in the structural, regulatory, and cultural rigidity of the existing built environment. Heritage-protection frameworks, fragmented ownership structures, and the lack of standardised digital material data continue to hinder the broader adoption of circular design principles. In this sense, the potential of circularity lies not merely in substituting materials or components, but in rethinking the building as a dynamic resource system [6].

These challenges are especially pronounced in culturally and landscape-sensitive territories, such as the sub-Apennine inland areas of Central Italy, where recurrent seismic events intersect with long-standing environmental and socio-economic fragilities. The most recent large-scale earthquake sequence in this region occurred in 2016–2017, when multiple high-magnitude events caused widespread destruction across vast inland territories. Historic settlements and critical infrastructures were severely damaged; tens of thousands of residents were displaced; and entire villages were partially or totally destroyed. The building stock—predominantly composed of unreinforced masonry—suffered extensive collapse, generating unprecedented volumes of rubble. Nearly a decade later, reconstruction processes remain markedly slow and fragmented.

In these regions, the built environment has traditionally relied on locally sourced materials that are deeply embedded in construction practices, landscape logics, and community identities. Within this setting, rubble assumes a dual and inherently contradictory role. On the one hand, it constitutes material evidence of local construction cultures, techniques, and resources; on the other, it represents a major operational and logistical constraint, as prolonged management and disposal processes have become critical bottlenecks that delay reconstruction and reinforce linear, waste-oriented approaches [7].

Existing research on post-disaster reconstruction and circular construction has progressively addressed rubble management from regulatory, environmental, and material perspectives [4]. Studies on the circular economy have emphasised the potential of treating the built environment as a reservoir of recoverable resources [6], while research on debris management has focused on recycling pathways, end-of-waste criteria, and environmental impacts [7]. More recent contributions have explored the role of digital technologies, material passports, and computational fabrication in enabling traceability and reuse [2,8]. However, these strands of research often remain fragmented, addressing material performance, regulatory frameworks, or digital processes in isolation. As a result, the integration of material characterisation, digital governance, and fabrication workflows within a unified reconstruction framework—particularly under post-disaster conditions marked by uncertainty and heterogeneity—remains insufficiently explored.

This paper addresses this systemic gap by introducing Rubble as a Material Bank (RMB), a highly experimental circular post-disaster reconstruction methodology developed at the School of Architecture and Design of the University of Camerino (Italy). RMB reconceptualises earthquake debris not as an inert by-product, but as a traceable and programmable material stream capable of supporting locally grounded, culturally coherent, and low-impact reconstruction processes. It defines a continuous rubble-to-component chain that links material characterisation and digital surveying with AI-supported sorting, robotic fabrication, and reversible architectural design: through digitally informed, automation-ready workflows, recovered resources can thus be selected, processed, and reintegrated into new construction.

RMB pursues a set of operational and cultural–territorial objectives articulated across two complementary domains. On the operational and methodological side, it aims to define a computational and material methodology capable of transforming the heterogeneity of seismic rubble into a knowledge-rich resource; to articulate an integrated rubble-to-component chain linking material data, digital processes, and fabrication workflows; and to validate selected downstream segments of this chain through the TRAP project, developed within the European TARGET-X programme. On the cultural and territorial side, the research seeks to demonstrate how material characterisation and digital traceability can function as the informational backbone of circular reconstruction, and to assess whether rubble-derived components can support culturally coherent reconstruction aligned with the material identity of sub-Apennine settlements.

From this perspective, Rubble as a Material Bank (RMB) reframes post-disaster reconstruction as a regenerative process in which rubble reuse is governed through a multi-layered informational and robotic infrastructure supporting digitally mediated reconstruction workflows. Nevertheless, Given the complexity of the topic, RMB is not conceived as a ready-to-deploy solution nor as a new material technology, but as an exploratory, process-oriented methodological framework. Building on existing research on circular construction, material banks, and post-disaster reconstruction, it integrates theoretical perspectives on material continuity and circularity with an experimentally validated workflow, with particular emphasis on the coordination between material characterisation, digital traceability, and robotic fabrication under post-disaster conditions.

2. The Materiality of Reconstruction

In disaster-affected inner territories such as the historic villages of Central Italy—characterised by vernacular construction systems based on locally sourced materials—post-earthquake reconstruction often takes place under conditions in which structural damage is so severe that repair is no longer feasible and, in some cases, even in situ rebuilding becomes impracticable. Extreme events may compromise the stability of settlement sites themselves, as in the case of Pescara del Tronto, in the municipality of Arquata del Tronto, on the border between the Lazio and Marche regions, where large portions of the village slid down the mountain ridge during the 2016 seismic sequence.

In such contexts, reconstruction cannot be reduced to the technical repair of collapsed structures, nor to the straightforward reproduction of pre-existing urban and architectural configurations, as suggested by the *as it was, where it was* paradigm [9]. When applied literally, this approach has shown clear limitations in territories marked by demographic shrinkage, evolving risk scenarios, and environmental constraints [5,10].

From this perspective, rubble can assume a strategic role: when reframed as a recoverable material resource rather than as waste, it may operate as a bridge between pre- and post-disaster conditions, preserving traces of local material cultures while enabling new reconstruction and territorial reconfiguration processes. As argued by Bianchi and Ruggiero [11], post-disaster reconstruction in inner areas thus constitutes a cultural and territorial operation in which continuity is not achieved through replication, but through the material rearticulation of disrupted landscapes, practices, and identities.

In post-disaster contexts, the stones, aggregates, and construction materials of collapsed buildings can become tangible carriers of continuity, anchoring collective memory

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and local identity when spatial layouts and architectural typologies are irreversibly altered [12]. Reconstruction thus extends beyond the restoration of spatial legibility, emerging instead as a process of material articulation through which communities renegotiate their relationship with place and landscape [8,13].

This interpretation expands the notion of architectural materiality beyond its conventional association with construction techniques or expressive languages. As argued by Picon [14], materiality constitutes a cultural and cognitive dimension through which architecture mediates environmental intelligence, historical sedimentation, and technological paradigms. In historically and landscape-sensitive post-disaster territories, materiality can therefore no longer be defined primarily through formal continuity or structural replication, but through the capacity of recycled and transformed materials to convey memory, territorial identity, and social meaning. From this standpoint, post-disaster reconstruction can be understood as an extension of Picon's concept toward a notion of recycled materiality, through which continuity after rupture is negotiated by means of material transformation.

On this basis, rubble is no longer interpreted as an inert residue to be removed, but as a material archive whose recharacterisation, reprocessing, and reintegration into reconstruction require informed and technologically mediated practices [8]. At the same time, this perspective foregrounds the intrinsic ambivalence of rubble, which simultaneously embodies a potential resource for material continuity and a substantial operational constraint within post-disaster reconstruction processes.

3. The Dual Nature of Rubble

Italy offers a particularly significant field of observation for post-disaster reconstruction in historically and landscape-sensitive inner territories, where seismic events have repeatedly affected settlements characterised by strong material identities and deeply sedimented construction cultures. In these contexts, rubble has rarely been approached as a material resource and has more often been treated as an obstacle to be removed to facilitate rapid rebuilding. As a result, reconstruction processes have frequently prioritised the replacement of damaged building stocks through new typologies and materials, often producing increasing material discontinuities with historically sedimented settlement systems [15].

This tendency is evident across several Italian reconstruction experiences. Following the 1980 Irpinia earthquake, continuity with local construction cultures was often set aside in favour of standardised building solutions [16]. Similar dynamics emerged after the 2009 earthquake in L'Aquila, where large-scale interventions introduced materials—such as timber-based systems—and residential typologies, including linear housing blocks, largely extraneous to the traditional masonry-based building culture and settlement patterns of the area [17]. A contrasting but equally illustrative case can be found in the Belice Valley after the 1968 earthquake, where rubble was assigned a powerful symbolic role through Alberto Burri's Cretto, crystallising destruction into a monumental act of memory, while reconstruction proceeded through the creation of an entirely new settlement detached from the material and spatial logic of the original town [18].

Taken together, these experiences highlight both the limitations and the missed opportunities associated with rubble management in post-disaster contexts, underscoring the need for a more systematic analysis, which is developed in the remainder of this chapter.

3.1. Rubble as Constraint

Earthquakes generate rubble at a scale and speed that far exceed those of ordinary demolition processes, a condition that becomes particularly critical in inner and mountainous territories characterised by limited accessibility and fragile logistical infrastructures.

The 2016/2017 Central Italy seismic sequence provides a paradigmatic example: approximately 2.7 million tons of rubble were produced almost instantaneously across hundreds of small settlements, overwhelming waste-management systems designed for gradual and predictable material flows and delaying emergency operations, especially in small sub-Apennine municipalities with limited spatial, organisational, and technical capacity [19].

These difficulties are further exacerbated by the fragmented territorial structure of Central Italy, marked by dispersed settlements, limited infrastructure, and complex administrative boundaries. In the absence of predefined pathways for disposal, recycling, or reuse, temporary storage sites are often identified ex post during the emergency phase and operate under provisional regulatory conditions, resulting in prolonged material immobilisation and persistent spatial and operational bottlenecks that delay reconstruction and constrain everyday territorial use [20].

Beyond logistical constraints, the material condition of seismic rubble represents a major limitation for reuse. Unlike controlled demolition waste, earthquake rubble is largely unsegregated and frequently contaminated (Figure 1), increasing the complexity and cost of sorting operations and often favouring disposal as the least demanding legal option, thereby reinforcing linear waste-management models [20]. Evidence from recycled aggregate production further indicates that, under certain conditions, processing mixed waste streams may be more expensive than sourcing natural aggregates, limiting the practical uptake of circular approaches in post-disaster reconstruction [21].

Figure 1. Heterogeneity of materials in a collapsed building following the 2016 Central Italy earthquake (Accumoli, RI), illustrating the mixed and unsegregated nature of seismic rubble that constrains reuse and circular processing.

Regulatory frameworks introduce an additional layer of constraint. Under Italian law, materials resulting from collapses and demolitions are generally classified as waste unless they can be directly sorted for reuse or recycling [19]. Although specific exemptions have been introduced in post-earthquake contexts, compliance with European End-of-Waste criteria remains difficult to achieve [22]. As a result, despite the formal adoption of the waste hierarchy mandated by the EU Waste Framework Directive [23], emergency regimes and material conditions often prevent its effective implementation, inhibiting the development of local circular material chains [21].

A further critical issue concerns the loss of material traceability during emergency clearance and handling operations [22]. As rubble is rapidly consolidated into heterogeneous stocks, information on origin, composition, and construction context is progressively erased, compromising both technical classification and the territorial and cultural specificity of materials. In reconstruction contexts where structural performance must be reconciled with landscape continuity and heritage values, this loss of provenance emerges as a structural barrier to culturally grounded circular practices [21].

Taken together, these conditions position rubble not merely as a waste stream, but as a multidimensional constraint that delays reconstruction, increases economic and environmental costs, and disrupts socio-material continuity. Recognising this complexity is a necessary step in reframing rubble management from an emergency-driven liability into a strategic component of circular, territorially grounded reconstruction.

3.2. Rubble as Resource

From an environmental perspective, the reuse and recycling of rubble as a secondary raw material can reduce greenhouse gas emissions associated with the quarrying, processing, and transportation of virgin aggregates, limit landscape degradation in already fragile territories, and reduce the demand for new landfill sites [24]. These benefits, however, depend on reprocessing strategies that effectively reintegrate materials into construction cycles at comparable or higher performance levels, rather than confining reuse to low-grade recycling pathways.

From an economic perspective, rubble is typically perceived as a cost, as transportation, sorting, and disposal impose a significant burden on public budgets, particularly in small municipalities [25]. When converted into certified secondary aggregates, however, these costs can be partially transformed into local value. In large-scale reconstruction contexts, the development of local processing chains can reduce dependence on external suppliers, support specialised enterprises, and foster technological clusters focused on debris valorisation.

The social dimension is equally significant. Circular processes based on rubble reuse can generate skilled employment in areas such as materials science, digital surveying, and robotic fabrication, helping to counter long-term depopulation trends in inner areas. Moreover, transforming the remains of collapsed buildings into new construction elements carries a strong symbolic charge, enabling communities to re-appropriate the tangible traces of disaster as instruments of regeneration.

In this perspective, upcycling plays a pivotal role. Defined as "a conversion process requiring creativity and design to transform waste into materials or products of higher environmental value" [26] (p. 358), upcycling in post-earthquake contexts must extend beyond environmental metrics to encompass cultural, social, and economic dimensions. While consolidated frameworks for circularity, such as the 10Rs ladder, prioritise minimal-intervention strategies [27], the heterogeneity and contamination of seismic rubble make transformative processes unavoidable.

Crushing, cleaning, and re-fabricating rubble into new components are more energy-intensive than direct reuse; however, such processes are often necessary to recover material meaning and continuity. In post-disaster territories, the exceptional nature of seismic destruction legitimises approaches in which environmental optimisation is balanced against symbolic regeneration and territorial cohesion. In this context, upcycling shifts from a purely technical strategy to a cultural and territorial one, capable of generating new material languages that reinterpret inner-area materiality without erasing its origins.

From this perspective, rubble is no longer understood as the inert terminus of a linear trajectory from crisis to landfill, but as the starting point of a circular and territorially grounded reconstruction model, in which environmental, economic, social, and cultural values are negotiated through informed design practices and digitally mediated material processes.

4. Rubble as a Material Bank (RMB): A Digital and Material-Based Method for Post-Disaster Reconstruction

4.1. Urban Mining and the Material Bank Concept

The constraints and opportunities associated with earthquake rubble reveal the limitations of conventional reconstruction paradigms, which remain largely focused on waste removal and material replacement and are therefore insufficient to address the material, environmental, and territorial challenges of post-disaster recovery. Within the broader field of circular construction strategies, concepts such as urban mining and material banks offer resource-centred approaches that can be meaningfully extended to reconstruction contexts, enabling the reintegration of debris into rebuilding processes.

Urban mining refers to the systematic extraction and management of materials embedded in the built environment, shifting attention from geological resources to anthropogenic material stocks [28]. Although traditionally applied to planned demolition and refurbishment, this approach is particularly relevant in earthquake-affected territories, where destruction generates large volumes of heterogeneous materials within short timeframes, providing a framework to redirect debris from disposal streams toward value-generating reconstruction processes (Figure 2).

Figure 2. Temporary storage of earthquake rubble in Central Italy (Accumoli, RI), highlighting the logistical and spatial constraints associated with debris management in inner and mountainous territories.

In post-disaster contexts, urban mining introduces a knowledge-based approach in which rubble is understood as a distributed material stock whose properties, composition, and potential applications require systematic assessment. This perspective supports reductions in environmental impacts, facilitates the reintroduction of secondary aggregates into local reconstruction cycles, and contributes to the preservation of material identity through localised reuse. To operationalise this shift, rubble must be treated not as an undifferentiated waste stream, but as a material bank [24].

4.2. Digitalisation as an Enabler of Circular Reconstruction

While industrial and policy narratives often frame digitalisation as a pathway to optimisation—aimed at reducing time, costs, and logistical complexity [29,30]—this productivity-oriented interpretation has increasingly been called into question. Recent studies emphasise the need for digital approaches that also address environmental impacts, labour reconfiguration, and contextual appropriateness, rather than efficiency gains alone [30,31].

In this broader perspective, digital tools do not operate as automated executors of predefined models, but as cognitive infrastructures capable of accommodating variability, irregularity, and incomplete information within design and construction workflows. The objective is therefore not automation per se, but the ability to model, manage, and govern complexity through fabrication-aware and data-rich processes [32,33].

Research on circular construction further shows that the reuse of materials across the built-environment system is often constrained less by technical feasibility than by discontinuities in information across actors, phases, and lifecycle stages [3–5,11]. In this sense, digitalisation becomes a key enabler of circular processes when it provides shared frameworks for identifying, documenting, and exchanging data on products and materials, as demonstrated by approaches such as the Circular Digital Built Environment and material-passport systems [34,35]. Complementary workflows that integrate reality capture, AI-supported identification and classification, and computational design rely on passports as a traceability layer to support material selection, processing, and reintegration [36,37].

This enabling role of digitalisation becomes particularly critical in post-disaster reconstruction contexts, where linear workflows and centralised supply chains are poorly aligned with the spatial dispersion of debris, the heterogeneity of materials, and the fragmented nature of affected territories. In such environments, digital infrastructures are not ancillary tools but necessary conditions for activating circular reconstruction practices that reconnect material flows, regulatory requirements, and territorial specificities.

To address the information discontinuities that typically constrain material reuse in these contexts, the Rubble as a Material Bank (RMB) framework adopts a flow-based information model in which rubble batches and fractions are progressively linked to mixes and discrete building elements through persistent identifiers and minimum datasets. In this contribution, the rubble-to-component chain is presented as the practical implementation of the RMB framework, and selected downstream segments of this chain are validated through prototype-based experimentation conducted within the TRAP project.

4.3. RMB: Framework and Workflow

Rubble as a Material Bank (RMB) is a research framework that translates repair-oriented approaches into contemporary reconstruction practices. Within RMB, debris is treated as a material archive that can be re-characterised, reprocessed, and reintegrated into new construction through verifiable and traceable pathways.

RMB is grounded in a coupled digital–material workflow in which operations such as surveying, sorting, and fraction selection, material characterisation, and fabrication are interconnected through structured data. Through this workflow, rubble is progressively transformed from an indeterminate mixed condition into a computable and governable material stream. This approach aligns with the logic of Digital Material Banks (DMBs), in which material value is preserved by retaining the knowledge required for present and future use.

The RMB framework defines a methodological approach for integrating rubble reuse, material characterisation, and data-driven management within post-disaster reconstruction processes. In this study, selected components of the RMB framework are experimentally investigated through the TRAP project, funded under the Horizon Europe TARGET-X programme (2024 call), which focuses on digital innovation in the construction sector enabled by 5G infrastructures. While TRAP provides a testbed for specific digital and operational aspects of RMB—such as data connectivity, real-time information exchange, and digitally assisted construction workflows—the overall RMB framework also encompasses material, regulatory, and territorial dimensions that extend beyond the scope of the TRAP experimentation.

4.4. Method and Objectives

Rather than testing predefined hypotheses, the study adopts an exploratory, process-oriented research design aimed at validating the feasibility and internal coherence of a digitally governed rubble-to-component workflow under post-disaster conditions.

Building on this research design, this section outlines the methodological framework adopted to implement local circularity in post-disaster reconstruction through the reuse of earthquake-generated rubble. The main objective is to enable the fabrication of building components of different nature—such as cladding elements, paving units, blocks, and other construction components—by reprocessing rubble-derived materials through extrusion-based additive manufacturing. In this approach, three-dimensional printing is not treated as an end in itself, but as a fabrication strategy capable of accommodating material variability, enabling controlled material transformation, and supporting the production of context-specific building components.

The Rubble as a Material Bank (RMB) framework addresses this objective by defining a rubble-to-component chain: an integrated digital–material workflow that transforms debris from an indeterminate mixed condition into a programmable material stream capable of supporting fabrication processes. Within RMB, the term rubble refers specifically to loose mineral-based construction materials generated by building collapse—such as stones, masonry fragments, bricks, and mixed aggregates derived from mortars and concrete—which constitute the predominant mass fraction of earthquake debris in historic masonry-based settlements. Discrete dry elements (e.g., timber components, steel profiles) are therefore excluded, as they follow different recovery logics, regulatory pathways, and reuse practices.

Focusing on lapideous and granular material streams, RMB addresses material flows that are typically regarded as low-value and difficult to characterise, yet that hold significant potential for circular reintegration when supported by appropriate digital, technical, and regulatory processes. Rather than optimising isolated operations, the rubble-to-component chain conceptualises reconstruction as the coordinated orchestration of material, informational, and territorial flows, in which each phase generates data that informs subsequent transformations and preserves material intelligence for future cycles.

Methodologically, the RMB workflow is structured around three interconnected domains—Material, Technology, and Design—linked by a cross-cutting layer of data continuity:

- Material, addressing the identification of rubble sources and fractions, the characterisation of lithotypes and key material descriptors, and the documentation of provenance as a proxy for territorial identity;
- Technology, defining the digital infrastructure required for passports and Digital Material Banks (DMBs), computational workflows, robotic extrusion supported by sensing and monitoring, and collaborative model exchange;
- Design, translating material and technological knowledge into fabrication-aware and reversible components, including toolpath constraints, tolerances, and assembly sequencing aligned with circular design principles;
- Data continuity (cross-cutting), ensuring persistent identifiers, logging schemas, and interoperability rules that link material descriptors, process records, and the digital representation of the assembled system end-to-end.

To support this process, the chain adopts an explicit information architecture through which design intent and process evidence travel with the material through nested objects:

- Batch = a traceable intake unit (source-defined)
- Fraction = a graded subset derived from processing/selection
- Mix = a printable formulation associated with a fraction set

- Element = a fabricated component instance
- Assembly position = as-built placement reference in the digital model

Upstream sourcing, sorting, and batch-level provenance remain part of the RMB framework but are not validated within the TRAP demonstrator and are treated as out of scope for the experimental evidence reported here (Figure 3).

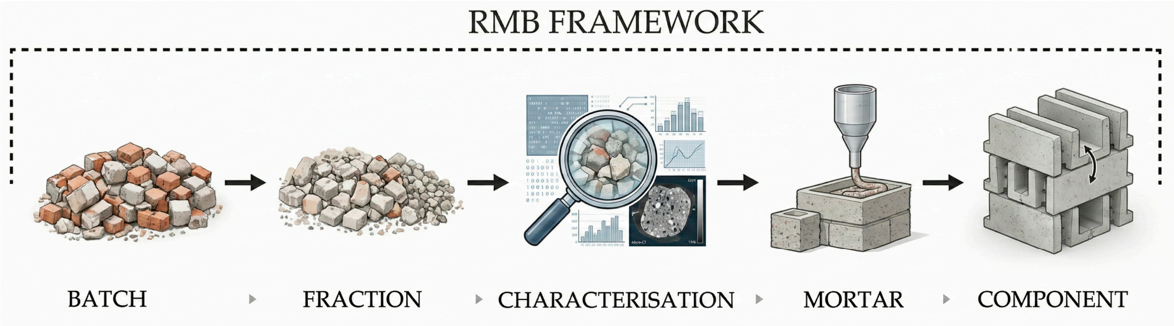

Figure 3. Rubble as a Material Bank (RMB) workflow, indicating the stages of the rubble-to-component chain considered within the TRAP experimental validation.

4.4.1. Material—Reframing Rubble as a Characterised Resource

In this framework, the Material domain focuses on transforming post-earthquake rubble from an indeterminate waste stream into a characterised and programmable resource. Seismic rubble is intrinsically heterogeneous, difficult to sort, and potentially contaminated; at the same time, it is closely linked to local lithotypes, construction traditions, and landscape cultures. The methodological objective is to preserve and formalise this material intelligence through systematic characterisation and the controlled definition of material fractions.

Material processing along the rubble-to-component chain includes selective sorting where feasible, controlled fragmentation (Figure 4), and laboratory testing aimed at generating decision-relevant datasets. Typical descriptors include granulometric distribution, density, porosity, water absorption, and compositional characteristics, while mechanical indicators may also be considered to support mix design and performance assessment. These datasets fulfil a dual role: they support potential regulatory compliance pathways (e.g., End-of-Waste-related requirements) and provide the epistemic basis for fabrication planning and computational modelling.

Given the lack of geometric regularity, material purity, and conventional traceability that characterise rubble, component-based material bank models are often unsuitable. For this reason, the methodology adopts a flow-based Digital Material Bank (DMB) organised around material attributes—physical, mechanical, environmental, and compositional—rather than discrete components. Within this framework, datasets function both as scientific records supporting experimental validation and as contextual records that preserve knowledge of the collapsed built fabric and its territorial provenance.

4.4.2. Technology—Building the Informational Infrastructure of Transformation

In the RMB framework, the Technology domain translates characterised material knowledge into actionable fabrication processes by establishing an informational infrastructure that governs variability, uncertainty, and heterogeneity—conditions intrinsic to rubble-derived material streams. Technology is therefore not conceived merely as a means of automation, but as the design of data structures, identifiers, and monitoring strategies that support traceability and informed decision-making along the rubble-to-component chain.

At the planning stage, digital technologies enable the classification, monitoring, and continuous enrichment of material data through reality capture, rule-based or AI-assisted identification, sensing systems, and structured databases. Processed batches and fractions can be associated with material passports, ensuring traceability and structured data updates as materials progress through selection, mix design, fabrication, and assembly stages.

Figure 4. Recycled aggregates obtained from earthquake rubble in Central Italy, used as granular input for rubble-based printable mortars.

Extrusion-based robotic fabrication is addressed as a rheology-governed technological infrastructure rather than a generic mechanisation step. When mortars incorporate recycled aggregates, coordinated control of interdependent parameters—such as extrusion pressure or equivalent pumping control, volumetric flow, deposition speed, interlayer time, and environmental conditions—is required. As highlighted in the 3D Concrete Printing literature, these coupled variables directly affect printability (Figure 5), mechanical performance, and failure modes, particularly in the presence of non-standard aggregates [38].

Figure 5. Example of failed extrusion-based 3D concrete printing, illustrating typical instability and buildability issues associated with non-standard or recycled aggregates.

The fabrication phase is supported by PLC-controlled mixing/pumping/dosing systems—integrated and automated units governed by a Programmable Logic Controller (PLC) that ensure coordinated control over material preparation and extrusion—combined with environmental monitoring. Fabrication generates process data (e.g., dosage proxies, flow control variables, pump torque or pressure where available, temperature and humidity, and timestamps), which can be logged and linked to element identifiers. Where proprietary parameters cannot be disclosed, proxy variables and observed ranges are reported to support comparability. Together, these datasets form the backbone of an evolving digital twin, recording geometry, material biography, and fabrication history at the element level.

4.4.3. Design—From Knowledge-Rich Matter to Reversible Components

The Design domain functions as the translational interface through which material characterisation and technological control are translated into architectural form. Design is conceived as a knowledge-driven process that integrates material intelligence (e.g., granulometry, rheological proxies, and mechanical indicators), fabrication constraints (such as bead geometry, anisotropy, and buildability), and reconstruction-specific requirements, including structural behaviour, compatibility with existing masonry logics, and reversibility.

Computational design tools are used to integrate heterogeneous inputs and negotiate constraints rather than to impose predefined typologies. Within this approach, discrete dry-assembled and reversible components are developed to operate within heritage-sensitive wall systems while meeting contemporary performance requirements. Geometries, joints, and cavities can be defined to facilitate assembly, accommodate reinforcement where required, and enable future disassembly, aligning with Design for Disassembly and Design for Recycling principles [39,40].

Each component is conceived as both a physical element and an informational asset. Through persistent identifiers, it is linked to its material passport, fabrication parameters, and assembly position within the digital twin. This dual status is essential to maintain traceability across the lifecycle and preserve the conditions for future adaptation, reuse, and material recirculation.

5. The TRAP Experiment: A Controlled Cyber–Physical Workflow

The TRAP test case implements the downstream segment of the RMB rubble-to-component chain (mix → element → assembly position) as a controlled cyber–physical workflow. The experimentation focuses on the fabrication of blocks (Figure 6) for a dry-assembled wall system; however, its primary objective is not the optimisation of the building product itself. Rather, the experiment is designed to investigate the processual dimension of post-disaster reconstruction, examining how material, data, and operational information can be coordinated across design, production, and assembly stages.

The workflow integrates parametric design and a BIM-based digital twin, robotic extrusion of discrete blocks, production monitoring with structured data logging, and Mixed Reality (MR) tools supporting storage management, assembly sequencing, and logistics verification. The experiment was conducted within the TARGET-X Trial Platform as a connectivity-enabled testbed, where the BIM digital twin functions as the coordinating reference model for distributing geometry and attribute data among design, fabrication, and assembly actors.

According to the validation boundary defined, the methods reported here address only downstream mechanisms and their measurable outputs. Upstream rubble sourcing, site-scale sorting, and batch-level provenance governance remain outside the experimental scope of TRAP and are therefore not used as evidence in this study.

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Figure 6. Robotic extrusion of a discrete block fabricated with a rubble-based printable mortar within the TRAP experimental setup.

5.1. Material Inputs, Mix Classification, and "Material Descriptor" Datasets

The TRAP demonstrator employed a printable cement-based formulation incorporating recycled aggregates, specifically developed for the robotic extrusion of modular blocks. Within the project reporting, the sustainability inventory of the printed material is documented using a cement specifically formulated for 3D printing as the binder and recycled aggregate as the primary granular input. The recycled aggregate fraction accounts for 30% of the printable mixture by mass.

To ensure traceable and comparable reporting under prototypical conditions, this study structures material inputs through a minimum material-descriptor dataset that records key physical and compositional attributes of rubble-derived materials. The dataset is designed to support informational continuity and interpretability along the rubble-to-component chain, rather than to provide full material certification. Accordingly, each tested material configuration is documented using a limited and consistent set of descriptors, including

- The binder system identifier (3D-printing-specific cement) and declared mix family;
- The aggregate class (recycled aggregate), including the maximum size class adopted in the demonstrator and in the printing tests reported in the appendices;
- The declared recycled content of the printable formulation;
- The minimum available physical descriptors derived from experimental records (e.g., density values used for pre-production calculations).

This approach provides a pragmatic basis for linking material composition to downstream fabrication indicators and sustainability accounting, while remaining compatible with the exploratory and process-oriented nature of the TRAP experimentation.

5.2. Software Infrastructure and Information Model (Data Continuity Implementation)

A BIM-based digital twin was adopted as the shared reference model for coordinating design, production, and assembly information across the TRAP workflow. Within this environment, data continuity was implemented through an integrated information model designed to maintain consistent links between digital representations and physical elements along the downstream rubble-to-component chain.

The information model relies on two coupled mechanisms: an element identification strategy that uniquely maps each physical block to a corresponding digital object and its intended assembly position, and a structured indicator schema that associates pre-production estimates, production logs, and assembly/logistics attributes with the same element identifier. Together, these mechanisms ensure traceability across stages and enable the aggregation and comparison of datasets generated at different points in the workflow.

5.2.1. Element ID Encoding and Mapping to Assembly Positions

Element-level traceability in TRAP is achieved through a positional–typological coding system that combines row and column indices with a block typology label (e.g., R08–C01–I). The row (Rxx) and column (Cyy) indices associate each block with its intended position within the wall layout, while the typology letter identifies the block family defined in the parametric design model.

The code is generated within the parametric environment, embedded as a parameter in the BIM-based digital twin, and used as a unique lookup key to associate production records, monitoring data, and assembly attributes with each block instance. This encoding strategy enables deterministic positioning, supports downstream logistics reasoning, and provides a stable reference for linking heterogeneous datasets.

5.2.2. Model Exchange and Synchronisation

Parametric modelling and workflow control were developed in Rhino/Grasshopper (version 8), which acted as the generative environment for element geometry and identifier assignment. Model and data exchange across heterogeneous platforms were implemented via Speckle (version 2) (Figure 7)—a cloud-based interoperability platform—used as a synchronisation layer enabling the iterative distribution of both geometry and per-element attributes.

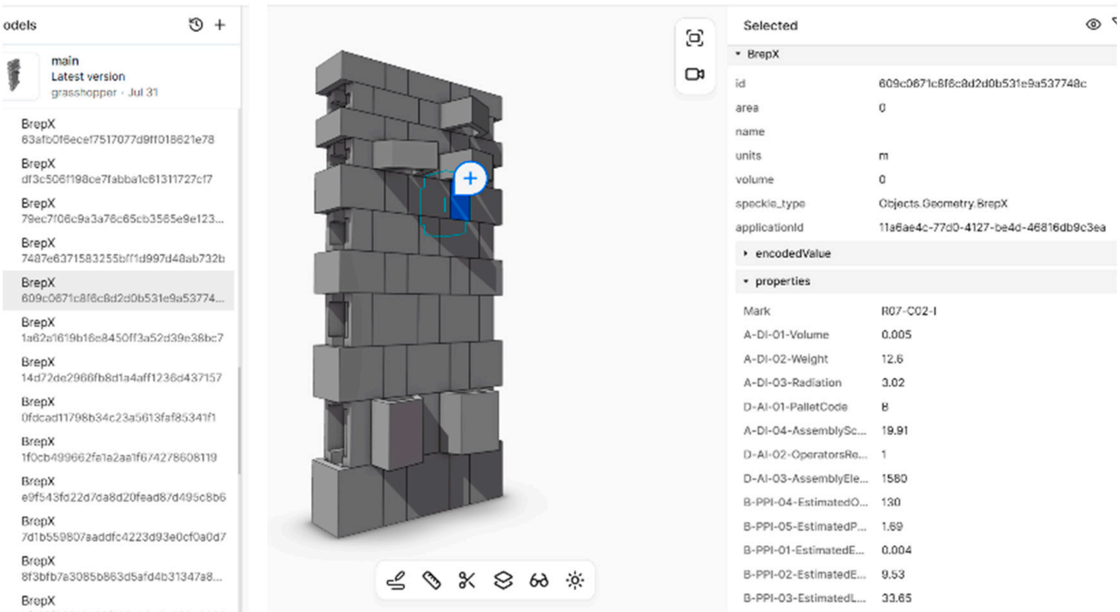

Figure 7. Model and data exchange workflow via Speckle, enabling synchronisation between parametric design, BIM-based digital twin, and downstream fabrication and assembly processes.

Within this architecture, Grasshopper operates as the source of parametric logic and ID generation, while Speckle propagates synchronised updates to the BIM-based digital twin and to Mixed Reality (MR) applications that consume the same attributes during storage and assembly simulations. This configuration supports bidirectional updates and maintains consistency across design, production, and downstream operational environments without requiring direct file-based interoperability.

5.3. Pre-Production Computation and Indicator Definition (PPI)

TRAP distinguishes pre-production indicators (PPI), derived from the digital model and toolpath estimates, from production indicators (PI) measured and logged during execution. PPI are computed using the production-setting parameters declared in the project development report—namely layer height (13.0 mm), nozzle diameter (20.0 mm), concrete density (2400 kg/m^3), nominal mass flow rate (6.3 kg/min), and robot speed (70–200 mm/s). Pre-production computations estimate:

- Printing time, based on toolpath length and speed assumptions;
- Extruded volume, calculated either from mass flow rate and time or from layer cross-sectional area and toolpath length;
- Extruded mass, obtained from volume–density relationships;
- Target geometric descriptors, such as element height derived from layer height and number of layers.

These indicators establish a quantitative baseline against which production measurements and logs are compared, enabling the assessment of deviation and supporting the interpretation of process stability and repeatability.

5.4. Robotic Production Cell and Execution Environment

Robotic fabrication was carried out within an integrated production cell combining a Yaskawa industrial robot for toolpath execution with an extrusion system designed for cement-based printing incorporating recycled aggregates and supplied by a mixing/pumping architecture (Figure 8). Toolpaths were simulated and verified in Rhino/Grasshopper using HAL Robotics (HAL Robotics Ltd., London, UK) (Figure 9)—a plugin for robotic programming and simulation—prior to execution, supporting collision avoidance, parameter calibration, and pre-production computations. Following the TRAP confidentiality framework, the methods report controllable parameters and observed ranges using a process-window approach, rather than disclosing proprietary thresholds. Subsystem-level settings (mixer, extruder, doser, pump) are treated as internal control variables and are reported only in terms of variable categories and adjustment logic where necessary for scientific interpretation.

5.5. Production Monitoring, Logging, and "Process-Window" Evidence Acquisition (PI)

Production monitoring was implemented through a PLC/HMI architecture, integrating dosing, mixing, water management, and extrusion subsystems. The PLC provides deterministic real-time control of the process, while the HMI supports operator interaction, supervision, and on-site process adjustment. Data were recorded with timestamps and exported in standard formats (CSV/JSON) to support both process interpretation and sustainability accounting, and to enable linkage to element IDs in the digital twin.

5.5.1. Logged Data Categories

Production-phase data is structured into two main dataset categories. The first comprises sustainability-oriented datasets supporting cradle-to-gate accounting, including material quantities, water consumption, electricity proxies, process duration and cycle times, and transport assumptions where relevant for inventory construction.

Figure 8. Robotic production cell used for the extrusion-based fabrication of rubble-derived components.

Figure 9. Toolpath simulation using HAL Robotics, supporting pre-production computation, collision checking, and fabrication planning.

The second category includes process and quality-control datasets used to interpret print stability and execution behaviour. These datasets consist of time-structured operation logs and measurable outcomes that can be evaluated against pre-production expectations, such as actual printing time, observed layer or bead-width consistency, and recorded element weights, where available.

In this study, the process window is defined as the combination of declared setpoints or admissible ranges for controllable parameters and the corresponding execution outcomes that demonstrate stable material deposition—such as continuous layer formation without collapse—under the tested conditions.

5.5.2. Association of Logs to Element IDs

Element-level traceability requires that each production record be unambiguously associated with the corresponding element ID. In TRAP, this association is achieved by embedding the element ID within the digital twin object and by structuring production records so that they reference the same identifier during data integration.

During the production phase, element-level segmentation of logs was implemented through operator-defined execution cycles, each corresponding to the fabrication of a single element. For each element, a dedicated production file was executed on the robotic system, ensuring that time-stamped logs, process parameters, and recorded outcomes could be consistently attributed to the associated element ID.

5.6. MR-Assisted Storage, Assembly Sequencing, and Logistics Verification

Mixed Reality (MR) was employed to support downstream handling and assembly tasks by visualising the digital twin and accessing element-level attributes—such as IDs, pallet codes, and weight-related handling parameters—during simulated storage and assembly operations (Figure 10). Two MR configurations were implemented in TRAP. The first used HoloLens 2 with Trimble Connect to visualise IFC-based BIM models and attributes, with spatial alignment achieved through printed QR codes placed at known reference points. The second adopted a Fologram workflow integrated with Meta Quest headsets, enabling a more flexible MR environment with real-time streaming from Rhino/Grasshopper and synchronisation via Speckle, supported by alignment through printed QR codes and ArUco markers.

MR procedures included spatial verification of the wall model within the testbed area, full dry-run simulations of block-by-block assembly sequencing, and simulated positioning of pallets and components for logistics reasoning. Furthermore, MR-based remote support scenarios—such as real-time instructions, action recording, and video streaming—were tested. Latency observed during high-bandwidth operations (e.g., model updates and streaming) was documented as a relevant limitation for potential field deployment.

5.7. Assembly/Logistics Indicators and Traceability Completeness Metrics

Assembly-related datasets were integrated into the digital twin to support traceability and logistics/safety management. The project reporting defines assembly indicators (AI, letter "D") compiled at element level, including

- D-AI-01 PalletCode: the identifier of the pallet in which the block is positioned;
- D-AI-02 OperatorsRequired: the number of people needed to lift the block manually, calculated using a maximum load of 25 kg per operator;
- D-AI-03 AssemblyElevation: the elevation in mm at which the block is to be installed, used to reason about work-at-height or lifting requirements.

Traceability completeness is evaluated as the coverage of persistent IDs and linked metadata across the downstream chain, i.e., the extent to which each element has: (i) an

ID defined in the parametric model and embedded in the digital twin, (ii) linked pre-production and production datasets, and (iii) an assembly-position reference and logistics attributes retrievable in MR.

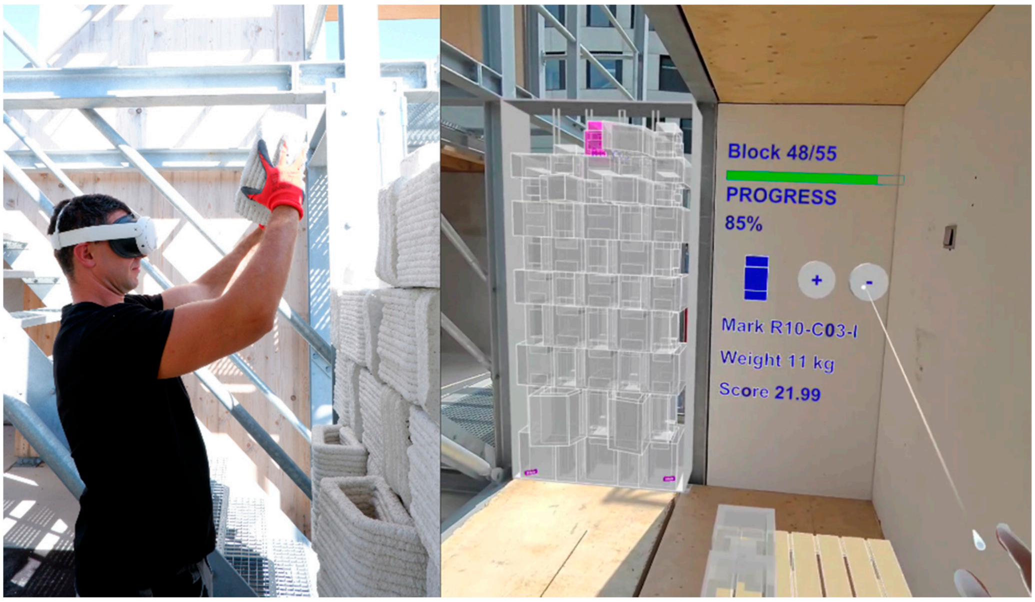

Figure 10. MR-assisted assembly process using a Meta Quest headset (Meta Platforms, Menlo Park, CA, USA) and Fologram (Fologram Pty Ltd., Melbourne, Australia), supporting element positioning, sequencing, and traceability within the digital twin environment.

5.8. Preliminary Cradle-to-Gate LCA Method

This section introduces a preliminary cradle-to-gate Life Cycle Assessment (LCA) approach designed to support the evaluation of reconstruction feasibility within circular post-disaster scenarios. Rather than aiming to deliver a comprehensive or fully standardised LCA, the proposed approach adopts a comparative and exploratory perspective intended to inform early-stage decision-making.

Within this framework, a preliminary cradle-to-gate LCA was conducted to assess the environmental impacts associated with the production of rubble-based components. The analysis focuses on selected phases of the rubble-to-component chain—specifically material processing and fabrication—and is based on simplified assumptions and experimentally available data. The considered indicators are derived directly from the experimental workflow and are used to highlight relative environmental trade-offs and operational constraints relevant to reconstruction feasibility.

5.9. Connectivity, Confidentiality, and Data Availability

TRAP was implemented as a connectivity-enabled workflow supporting synchronisation across design, production, storage/assembly, and remote supervision. Project documentation indicates that MR streaming and model-update operations are sensitive to latency and bandwidth and therefore benefit from optimised network architectures, such as edge processing and simplified network configurations.

Given industrial confidentiality constraints, this manuscript reports only non-sensitive parameter categories, value ranges, and decision criteria sufficient for scientific interpretation. Proprietary thresholds and exact control values are not disclosed. Where feasible, aggregated or anonymised datasets—such as per-element indicators excluding sensitive machine settings.

6. TRAP—Experimental Validation of the Chain

The experimental verification presented in this study focuses on validating the feasibility, robustness, and interoperability of the rubble-to-component workflow, rather than on the comprehensive mechanical characterisation of the produced materials. The experimental activities are therefore oriented towards process validation, fabrication consistency, and integration across digital, material, and robotic stages. Detailed mechanical testing and standardised material characterisation are beyond the scope of this paper and are identified as part of ongoing and future research.

In the Rubble as a Material Bank (RMB) framework, the TRAP (Remote-controlled Assembly Process) project provides an experimental validation of the downstream segment of the rubble-to-component chain, with specific focus on the Technology–Design interface. Funded under the European TARGET-X programme (Trial Platform for 5G Evolution), TRAP operates as a cyber–physical testbed aimed at assessing the feasibility, robustness, and limitations of digitally integrated workflows for construction processes under real-world, connectivity-enabled conditions.

In this context, TRAP does not address the full scope of rubble management but concentrates on the phases in which characterised material streams are transformed into fabricable elements and subsequently assembled through digitally coordinated processes.

The value of the TRAP experimentation lies primarily in the validation of the workflow, rather than in the architectural outcome. The Green5Wall dry-assembled wall system is therefore conceived as a demonstrator, intended to test the operability, internal coherence, and critical thresholds of the proposed rubble-to-component chain, rather than as a finished construction solution designed for direct replication. The experiment investigates how rubble-derived aggregates, once characterised and digitally governed, can be reprocessed into discrete components through extrusion-based fabrication and assembled within a reversible system.

A first level of validation concerns the alignment between digital design intent and material behaviour. Parametric design tools were used to define component geometries, toolpaths, and assembly sequences based on material descriptors and simulated fabrication constraints. These digital assumptions—relating to layer geometry, tolerances, and assembly fit—were then confronted with the observed behaviour of rubble-based mortars during robotic extrusion. Deviations between expected and actual performance, including variations in dimensional accuracy, surface quality, and buildability, were captured and documented within the digital twin. This comparison confirms the role of digital design not as a prescriptive model, but as a mediating layer capable of accommodating uncertainty and negotiating the intrinsic variability of recycled aggregates.

A second validation dimension addresses the capacity of robotic extrusion systems to operate with variable, rubble-derived feedstocks. Unlike industrial mortars with tightly controlled compositions, mixes incorporating recycled aggregates exhibit variability in granulometry, absorption, and rheological response. Within TRAP, robotic fabrication was executed in a dedicated production cell equipped with a six-axis industrial robot and an extrusion system capable of processing mortars containing recycled aggregates up to 8 mm. Key process parameters—such as extrusion flow rate, deposition speed, interlayer timing, and environmental conditions—were monitored and adjusted in real time. The experimentation demonstrates that stable deposition can be achieved despite material heterogeneity, provided that fabrication parameters are continuously calibrated based on material response and process feedback.

A third validation dimension concerns the role of digital twins and data continuity in maintaining traceability across fragmented workflows. Each fabricated block was assigned a persistent identifier linking its digital representation to material descriptors, pre-production estimates, and production logs. Process data—including flow-related proxies, pump and extrusion metrics, and environmental conditions—were synchronised with the digital twin, enabling element-level correlation between fabrication parameters and observed behaviour within the assembled system. This data continuity supports quality control, post-fabrication assessment, and the potential for future disassembly and reuse, reinforcing the role of digital infrastructures as enabling conditions for circular reconstruction.

A final validation dimension addresses the integration of digitally assisted assembly processes. The assembly of the Green5Wall prototype was supported through Mixed Reality (MR) interfaces connected to the same digital twin used for design and fabrication. MR tools provided placement guidance, sequence verification, and tolerance control, demonstrating how digitally mediated assembly can compensate for geometric variability and support dry, reversible construction systems. The connectivity framework provided by TARGET-X enabled synchronisation between design models, fabrication data, and on-site operations, allowing real-time supervision and coordination across stages.

The TRAP experiment does not exhaust the rubble-to-component chain. Upstream phases—such as large-scale debris management, selective deconstruction, and full regulatory consolidation—remain outside the scope of the study. Nevertheless, the project validates a central hypothesis of the RMB framework: once characterised and digitally governed, rubble can be transformed into a knowledge-rich material stream capable of supporting fabricable, reversible, and territorially grounded construction processes. At the same time, TRAP exposes technical, organisational, and regulatory limitations, providing a critical basis for refinement, scaling strategies, and future research on circular reconstruction in earthquake-affected inner territories.

7. Results and Discussion

The results are reported in terms of experimentally observable outcomes rather than conventional performance metrics. These include the feasibility of fabricating rubble-based components, the stability of the extrusion process under variable material conditions, the continuity of data and traceability across workflow stages, and the operability of digitally assisted assembly procedures. Taken together, these outcomes provide empirical evidence of both the potential and the current limitations of the proposed rubble-to-component chain.

The experimental outcomes of the TRAP project provide a basis for critically assessing the gap between current post-disaster reconstruction practices and a possible transition towards circular, digitally enabled, and territorially grounded models. Despite the growing recognition of the built environment as a reservoir of material resources and cultural knowledge [2], post-earthquake reconstruction still predominantly follows linear logics, in which collapse marks the beginning of a waste-management trajectory rather than a regenerative process.

In this context, the experimental validation of the rubble-to-component chain offers partial but concrete evidence that this paradigm can be reconfigured, particularly in inner territories where seismic events generate what Clemente and Salvati [9] describe as "interrupted landscapes", simultaneously affecting material continuity, spatial legibility, and social cohesion.

Rather than introducing independent findings, this section interprets the experimental results in relation to the underlying mechanisms of the proposed rubble-to-component framework. The results indicate that reconstruction feasibility is not determined by isolated material performance, but by the interaction between material heterogeneity, digital traceability, and process integration. Accordingly, the observed outcomes can be understood as the result of a systemic configuration, in which data-driven selection, controlled fabrication, and workflow interoperability collectively enable the reuse of seismic rubble within circular reconstruction scenarios.

Building on this interpretation, the discussion is structured around three analytical dimensions emerging from the experimental results: (i) process coherence across material, digital, and fabrication stages; (ii) operational and regulatory constraints that currently limit scalability; and (iii) implications for territorial continuity and architectural identity. These dimensions frame the interpretation of the experimental findings in relation to existing literature and to the specific conditions of post-disaster reconstruction, structuring the core analytical discussion (Sections 7.1–7.3). The subsequent subsections (Sections 7.4–7.6) provide a transversal synthesis, a critical assessment of the current level of validation, and a broader interpretative outlook on the implications of the proposed framework.

7.1. Digital Innovation as an Enabler—Not a Simplifier—Of Circular Reconstruction

While previous studies on digital fabrication and circular construction often emphasise material optimisation or productivity gains, the present findings indicate that, in post-disaster contexts, the primary value of digitalisation lies in its capacity to manage uncertainty and heterogeneity.

The TRAP experiment confirms that digital innovation enables circular reconstruction not by reducing complexity, but by rendering it governable. Robotic extrusion, sensor-informed process control, and digital twin infrastructures show that material heterogeneity—traditionally regarded as a limiting factor—can be incorporated as a computational variable within fabrication workflows.

The feasibility of printing mortars containing rubble-derived aggregates further demonstrates that uncertainties associated with recycled materials can be addressed through real-time calibration, particularly when parameters such as granulometry proxies, extrusion flow, deposition speed, and environmental conditions are continuously monitored and logged. This observation aligns with established positions in computational fabrication research, which frame digital technologies as mediating systems capable of negotiating material behaviour rather than merely executing predefined forms [38,41–43].

Rather than "optimising" reconstruction in an industrial sense, digital tools enable construction processes to operate under conditions of fragmentation, resource scarcity, and heritage sensitivity typical of Apennine inner areas. In this way, they support forms of material repair that incorporate—rather than erase—the material consequences of collapse.

7.2. Material and Regulatory Bottlenecks: The Obstacles Ahead

Despite these results, several structural bottlenecks remain evident.

First, the processing cost of rubble-derived aggregates remains high. Contamination, soil admixture, and irregular granulometry require washing, screening, and repeated sorting, increasing both energy demand and operational complexity, in line with previous analyses of post-disaster debris management.

Second, the instability of material flows poses a significant challenge. Earthquake rubble emerges suddenly and unpredictably, conflicting with the stable input assumptions underpinning most recycling plants and End-of-Waste certification pathways.

Third, technological limitations of current extrusion systems constrain geometric resolution. Although the TRAP blocks support dry and reversible assembly, extrusion-based processes do not yet reproduce the stereotomic richness or morphological variation characteristic of historic masonry, echoing concerns raised by Picon [14] regarding the risk of material homogenisation.

Finally, regulatory misalignment persists. Seismic codes, heritage prescriptions, and waste regulations remain compartmentalised, offering limited support for hybrid workflows in which rubble is transformed, certified, and reintegrated into construction within the same territorial cycle. These constraints do not invalidate the proposed process, but they clearly define its current operational boundaries.

It is important to clarify that the proposed framework is not intended for immediate emergency-response phases, which prioritise speed, safety, and debris clearance under highly constrained conditions. Instead, the rubble-to-component approach is conceived for the transitional phase between emergency management and long-term reconstruction, when material flows become more stable and digitally governed processes—such as traceability, fabrication planning, and coordinated assembly—can be meaningfully implemented.

7.3. Compatibility with Territorial Identity and Architectural Continuity

A key question emerging from the experiment concerns the compatibility of rubble-derived components with the identity of historic settlements. The TRAP demonstrator suggests that continuity can be maintained when material provenance is documented, chromatic responses reflect local lithotypes, and modular, reversible geometries resonate with long-standing seismic construction logics.

At the same time, relevant limitations emerge. Surface regularity associated with extrusion, mechanical anisotropy, and reduced textural variation introduce perceptual and cultural distances from traditional stonework. These findings indicate that circular reconstruction should not aim at literal replication, but at contextual continuity, in which technological transformation is negotiated within the material logic of place rather than imposed upon it.

7.4. From Prototype Validation to a Systemic Model

Overall, the results place the rubble-to-component chain at an intermediate level of validation. While the conceptual framework is supported by experimental evidence at the component and workflow scales, it has not yet been tested at systemic or territorial levels.

At present, the chain can be considered partially validated. Material characterisation protocols are available, although they require further standardisation; computational workflows for modelling, fabrication, and traceability are operational; reversible block families have been successfully produced and assembled; and digital twin infrastructures demonstrate that material biographies can persist across multiple lifecycle stages.

Scaling beyond the prototype, however, requires conditions that extend well beyond the laboratory. These include regulatory frameworks capable of recognising transformed rubble as a legitimate construction resource, mobile processing infrastructures suited to mountainous territories, reduced energy costs for aggregate preparation, and stronger alignment between digitally fabricated components and the cultural landscapes of Italy's diffuse settlement system.

Beyond technical feasibility, implementation is strongly conditioned by organisational and workforce-related factors. Digitally governed rubble reuse requires new professional profiles combining material knowledge, digital modelling, fabrication supervision, and on-site coordination supported by mixed-reality tools. In addition, clear institutional responsibility for material data governance and inter-actor coordination emerges as a critical requirement. These organisational and skill-related factors represent significant barriers to real-world deployment and must be addressed alongside technical validation.

7.5. How Far Are We?

The results indicate that circular reconstruction based on rubble reuse is technically feasible, but not yet institutionally consolidated, economically stable, or culturally embedded. In Technology Readiness Level (TRL) terms, the rubble-to-component chain currently lies between TRL 4 and TRL 6: validated in controlled settings and partially demonstrated in relevant environments, but not ready for full territorial deployment.

At the same time, the trajectory is clear. The experiment reframes rubble from an inert residue of destruction into a knowledge-rich material stream; demonstrates the role of digital tools as cognitive infrastructures for managing uncertainty; and suggests that reconstruction can evolve into a project of continuity rather than replication.

7.6. Towards a New Material Ecology of Reconstruction

The broader implication is that reconstruction in fragile inner territories can no longer be conceived as an exceptional response relying solely on external resources. Instead, it must evolve into a material ecology, in which local matter, digital intelligence, cultural memory, and reversible design converge to support long-term territorial resilience.

If rubble represents the final material layer of collapsed settlements, rebuilding with rubble—characterised, transformed, and digitally governed—means weaving past and future into a continuous material narrative. This approach is neither nostalgic nor technologically deterministic; rather, it operationalises the condition of polycrisis, as theorised by Morin and Kern, by framing reconstruction as a materially grounded and context-sensitive response to contemporary landscape transformations [44].

The empirical support of this study is grounded in experimental process data, workflow validation outcomes, and feasibility-oriented indicators rather than conventional performance metrics. Accordingly, the results do not seek to replicate or contradict existing quantitative findings on rubble-based materials, but to complement them by addressing dimensions that remain underexplored in the literature, namely process integration, operational constraints, and data-driven coordination across reconstruction stages. In relation to existing studies on circular construction, material banks, and digital fabrication, the findings are consistent with established theoretical frameworks, while extending them by demonstrating how such principles can be operationalised under post-disaster conditions characterised by uncertainty, heterogeneity, and fragmented data.

8. Conclusions

The conclusions presented here are grounded in the experimentally validated workflow and in the process-based results discussed in the preceding sections, and are interpreted in relation to the existing literature on circular construction and post-disaster reconstruction.

This study demonstrates that post-disaster reconstruction in earthquake-affected territories can be rethought through a circular and territorially grounded approach in which rubble, traditionally treated as waste, functions as an active material resource. Through the definition and partial experimental validation of the rubble-to-component chain within the TRAP project, the research shows that digitally governed fabrication workflows can transform heterogeneous debris into traceable and fabricable construction components. The findings indicate that the feasibility of circular reconstruction does not depend on isolated material performance but emerges from the interaction between qualified material characterisation, the digital governance of heterogeneity, and reversible architectural systems capable of mediating continuity and transformation in heritage-sensitive contexts.

At the same time, the study identifies a set of conditions that are critical for broader adoption. Regulatory frameworks must evolve to recognise transformed rubble as a legitimate construction resource; processing infrastructures and professional skills need to adapt to the constraints of fragmented inner territories; and the cultural acceptance of new material expressions requires active institutional and social support. While these considerations are grounded in the Central Italy case, they are also relevant to other regions worldwide characterised by structural vulnerability, resource scarcity, and increasing climate stress. From this perspective, rubble can be reframed from a residual outcome of destruction into the starting point of a new material ecology, in which digital intelligence, cultural memory, and reversible design converge to support regenerative reconstruction pathways.

The contribution of this study should therefore be interpreted in relation to its process-oriented scope. Structural performance, seismic resistance, and emergency-phase applicability were not experimentally assessed. Nevertheless, the proposed framework provides empirical evidence of how digitally governed workflows can enable rubble reuse within circular reconstruction strategies. The value of the research thus lies not in delivering a ready-to-deploy construction solution, but in articulating and validating a coherent methodological pathway capable of informing subsequent technical, organisational, and regulatory developments.

9. Limitations and Directions for Future Research

The limitations of this study are consistent with its exploratory and process-oriented scope and should be interpreted in relation to the specific objectives pursued.

First, the research does not include experimental testing of long-term durability, mechanical behaviour, or seismic structural performance of the fabricated components. The proposed elements should, therefore, not be interpreted as structurally certified solutions for post-earthquake reconstruction but as process demonstrators developed to validate the feasibility and internal coherence of a digitally governed rubble-to-component workflow. Structural qualification, seismic validation, and compliance with performance-based design requirements remain essential steps for any future deployment at building scale.

Second, the study does not provide a quantitative comparative assessment against conventional rubble recycling practices or prefabricated construction systems in terms of cost, speed, or structural performance. This choice reflects the focus of the research on process logic rather than on optimisation metrics. The proposed framework prioritises material traceability, circular governance, and territorial continuity—dimensions that are not directly comparable with approaches primarily driven by standardisation or short-term efficiency criteria.

Third, the framework has not been validated under emergency-phase conditions. Experimental testing was conducted in a controlled environment and therefore does not represent the operational constraints typical of immediate post-disaster response, including extreme time pressure, safety-critical conditions, and unstructured debris clearance. The proposed approach is instead conceived for the transitional phase between emergency management and long-term reconstruction, when material flows stabilise and digitally mediated processes can be meaningfully implemented.

Fourth, the implementation of the proposed workflow entails significant organisational and workforce implications that are only partially addressed in this study. The shift towards digitally assisted fabrication, data-driven material management, and mixed-reality-supported assembly introduces new skill requirements, coordination models, and institutional responsibilities. These aspects constitute substantial barriers to real-world adoption and require further investigation involving public authorities, construction actors, and training institutions.

Finally, the environmental assessment presented in this study is partial. While it addresses material processing and fabrication stages, it does not comprehensively account for the environmental impacts associated with digital infrastructures, including computing resources, sensing systems, data management, and connectivity. These impacts are acknowledged as a limitation and should be integrated into future, more comprehensive life-cycle assessments.

Taken together, these limitations do not undermine the validity of the proposed framework; rather, they define its current operational boundaries and delineate a research agenda for further development, validation, and potential scaling.

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Conflicts of Interest: The authors declare no conflict of interest.

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