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Structuring Sustainability-Oriented Reconstruction Decisions After Earthquakes: A MIVES-Based Methodological Framework

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Abstract

Post-earthquake reconstruction involves complex decision-making that extends beyond structural safety to include economic, environmental, and social considerations under conditions of uncertainty and limited resources. Although sustainability-oriented assessment frameworks and multi-criteria decision-making approaches have increasingly been applied in disaster contexts, existing models typically address localized technical interventions and rarely support strategic reconstruction planning after earthquakes. This study develops a sustainability-based decision-support framework for post-earthquake reconstruction of reinforced concrete buildings using the Integrated Value Model for Sustainability Assessment (MIVES). This framework is derived through a systematic synthesis of the post-earthquake, post-disaster, and MIVES-based literature. Reconstruction alternatives reported in previous studies are first identified and classified to structure the reconstruction decision space. Sustainability requirements, criteria, and indicators are then examined and adapted through processes of retention, modification, elimination, and addition. The principal outcome of the study is an adapted MIVES requirements tree composed of 10 criteria and 19 indicators organized across the sustainability dimensions, providing a context-consistent hierarchical structure for strategic building-level reconstruction decisions. By explicitly linking reconstruction alternatives with sustainability indicators within clearly defined decision boundaries, the framework strengthens methodological rigor in sustainability-oriented reconstruction planning. The present article focuses on the methodological development of the framework (Part I). The operational implementation of the model—including expert-based weighting, value-function definition, indicator aggregation, and empirical validation through case studies—will be presented in a companion study. The proposed framework provides a transparent and transferable basis for sustainability-oriented reconstruction planning and supports informed decision-making by public authorities.

Keywords: post-earthquake reconstruction; sustainability assessment; multi-criteria decision-making; reconstruction planning; reconstruction alternatives

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1. Introduction

Recent earthquakes have continued to generate extensive and recurrent damage to the built environment worldwide [1]. Recent global disaster assessments report that individual seismic events can affect tens to hundreds of thousands of buildings. According to the recent Global Assessment Report on Disaster Risk Reduction in 2023 [2] and 2025 [3], earthquake-induced damage to buildings remains a major global risk. Since 2020, several major seismic

events have highlighted the persistent scale of earthquake-induced building damage. A summary of representative recent events and their associated impacts is presented in Table 1.

Table 1. Summary of recent major earthquake events and associated building damage (2020–2024).

Event	Location	Year	Estimated Building Damage	References
Aegean Sea earthquake	Turkey–Greece	2020	>4000 buildings affected	[4]
Haiti earthquake	Haiti	2021	~60,000 buildings destroyed or severely damaged	[5–8]
Turkey–Syria earthquakes	Turkey–Syria	2023	>230,000 buildings collapsed or severely damaged; ~1.9 million housing units affected	[9–14]
Al Haouz earthquake	Morocco	2024	~59,000 buildings damaged	[15–19]
Peninsula earthquake	Japan		More than 70,000 buildings	[20–23]

Together, these events demonstrate that earthquake-induced building damage remains both recurrent and large-scale, generating substantial long-term reconstruction demands [24]

In disaster-affected and resource-constrained environments [14,20], the magnitude of damage typically exceeds the capacity of individual building owners to respond independently [4,16,17]. Post-earthquake reconstruction, therefore, becomes a public responsibility, requiring coordinated action by governments and public institutions [25]. Public authorities must prioritize interventions [26]; allocate limited resources; coordinate multiple stakeholders; and define reconstruction strategies that ensure safety, habitability, and recovery over time [27,28]. Such decisions are frequently made under conditions of uncertainty, time pressure, and incomplete information. Consequently, post-earthquake reconstruction becomes a strategic decision-making challenge at the policy and planning levels rather than a purely technical task [29,30].

Although engineering-based assessments are indispensable for ensuring structural safety and minimum habitability [31], post-earthquake reconstruction practice has historically been dominated by technical evaluations focused on damage classification [32], seismic vulnerability, and code compliance [29,33]. However, these assessments alone are insufficient to guide reconstruction decisions with long-term environmental, economic, and social implications [34,35]. Reconstruction choices influence material consumption and waste generation, recovery duration and economic viability [28], as well as social conditions such as displacement, accessibility, and community cohesion [36]. As a result, sustainability has increasingly been promoted as a guiding principle for post-disaster reconstruction [37]. This perspective seeks to balance safety, functionality, environmental responsibility, economic feasibility, and social well-being over the long term [12,28,38].

Despite this growing emphasis, sustainability-oriented approaches to post-earthquake reconstruction remain fragmented [39]. Reconstruction alternatives are rarely structured as an explicit decision space [40]. Many studies instead focus on isolated technical interventions rather than coherent strategic options such as repair, strengthening, demolition and reconstruction, relocation, or preservation [27,38]. At the same time, sustainability indicators are often selected independently of the reconstruction alternatives they are intended to evaluate. As a result, economic, environmental, and social dimensions are rarely integrated within a unified assessment structure [35]. These limitations are particularly critical in post-earthquake contexts, where public authorities must make rapid, high-impact decisions under constrained resources and uncertainty [9].

To address these challenges, this research develops a sustainability-based decision-support framework for post-earthquake reconstruction through the adaptation of existing

multi-criteria assessment models, rather than the creation of a new assessment paradigm. The framework is derived from established sustainability decision-support methodologies and is specifically adapted to the strategic reconstruction decision level. The present article focuses on the methodological development of this framework. It includes the structured identification of post-earthquake reconstruction alternatives and the adaptation of sustainability requirements, criteria, and indicators. The remainder of the article is organized as follows. Section 2 presents the state of the art on post-earthquake reconstruction and sustainability-oriented decision-making. Section 3 describes the methodological framework adopted for model adaptation. Section 4 presents the resulting sustainability assessment structure. Section 5 discusses the findings and methodological implications. Section 6 concludes the paper and outlines directions for future research.

2. State of the Art

The state of the art in this study is established through a structured literature review of 73 open-access, English-language studies published between 2015 and 2025, identified using combinations of the keywords: sustainability, post-earthquake reconstruction, post-disaster recovery, decision-making, reconstruction alternatives, and building damage. The literature search is conducted across three databases: Scopus [41], Web of Science [42], and Google Scholar [43]. Scopus and Web of Science are selected for their high indexing standards, peer-reviewed coverage, and metadata filtering capabilities, while Google Scholar serves as a supplementary source to capture regional or gray literature, especially from post-war environments where formal academic publishing may be constrained. The reviewed literature reflects a rapidly expanding research field addressing the reconstruction of damaged buildings after disasters. Rather than providing an exhaustive literature review, the purpose of this synthesis is to identify the methodological patterns and sustainability dimensions that inform the construction of the proposed framework. At the same time, it reveals substantial methodological, conceptual, and structural fragmentation, particularly with respect to decision-making at the strategic reconstruction level. The complete list of the reviewed studies included in the state-of-the-art analysis is provided in Appendix A (Table A1), where each study is also classified according to its contribution to the reconstruction alternative space discussed in Section 4.3.

A first distinguishing feature of the reviewed literature concerns the methodological approaches employed. As illustrated in Figure 1, quantitative and engineering-based studies remain predominant [44], especially those focused on seismic damage assessment, structural vulnerability analysis [25], retrofit performance, and code compliance [33,45,46]. These studies provide indispensable technical foundations for post-earthquake reconstruction [30], yet they typically address reconstruction from a performance or compliance perspective and do not explicitly frame reconstruction as a choice among alternative strategies [26,40]. Alongside these, a growing body of research applies multi-criteria decision-making (MCDM) and decision-support approaches to post-disaster problems such as housing solutions, retrofit prioritization, site selection, and project ranking [33,35,47–51]. While these approaches enable structured comparison across multiple criteria, they often rely on predefined alternatives and indicator sets, limiting their adaptability to the heterogeneous and uncertain conditions characteristic of post-earthquake reconstruction [33,52]. In parallel, qualitative and conceptual studies—particularly in post-conflict, governance, and heritage-related contexts—provide valuable insights into recovery principles, institutional dynamics, and social processes [53–59] but generally lack operational mechanisms for systematic comparison of reconstruction options. Systematic reviews and mixed-method studies remain comparatively scarce [28,39], highlighting the absence of consolidated methodological structures capable of supporting strategic reconstruction decision-making.

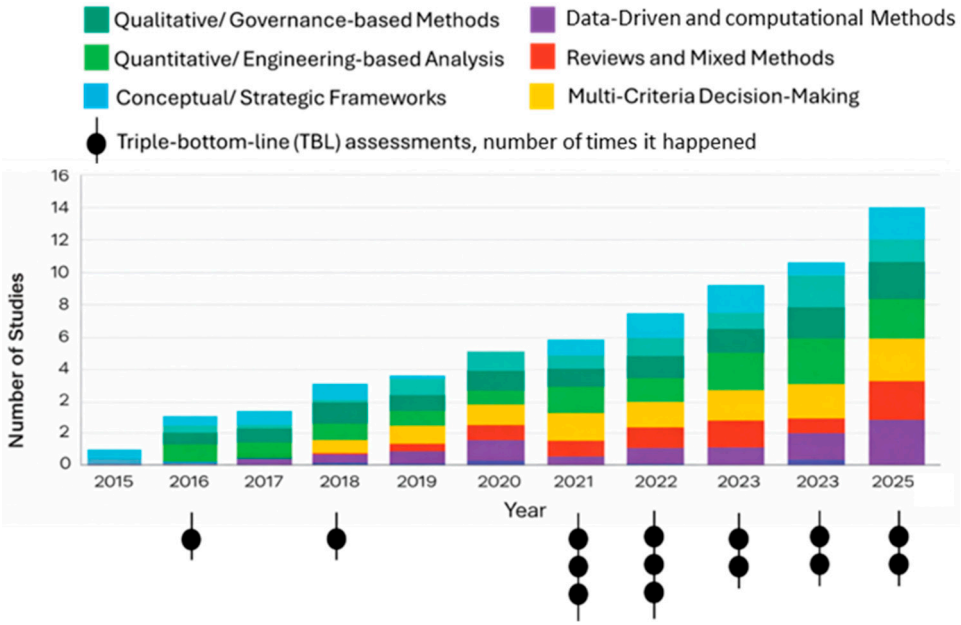


Figure 1. Temporal distribution of methodological approaches adopted in post-earthquake reconstruction studies published between 2015 and 2025, with overlay of triple-bottom-line (TBL) assessments per year (n = 14).

Beyond methodological diversity, the literature exhibits a clear imbalance among sustainability dimensions. Environmental aspects—including energy performance, embodied emissions, material consumption, and waste generation—are most frequently addressed [34,35,39,51,60–63]. Economic considerations, such as reconstruction cost, financing mechanisms, and long-term economic feasibility, are also widely examined, particularly in studies related to infrastructure renovation and investment management [64–66]. In contrast, social sustainability dimensions—including occupational safety, community participation, social acceptance, and cultural value—are addressed less consistently and are often treated in isolation from economic and environmental criteria [49,52,67–70]. Although recent studies increasingly advocate integrated sustainability perspectives, fully integrated triple-bottom-line assessments remain the exception rather than the norm, as illustrated in Figure 1 [47,49,52,71].

The temporal distribution of the reviewed studies further highlights an evolution in research focus over the past decade, as illustrated in Figure 1. Earlier contributions predominantly emphasize technical assessment and engineering performance, whereas sustainability-oriented and decision-support approaches become increasingly prominent after 2020 [28,68,72–75]. This shift reflects growing recognition of the long-term environmental, economic, and social consequences of reconstruction decisions. However, this diversification of methods has not been accompanied by a corresponding consolidation of reconstruction decision frameworks, resulting in research characterized by parallel and often disconnected analytical approaches.

Across methodologies, sustainability dimensions, and publication periods, several recurring patterns can be observed in the literature [72]. Reconstruction alternatives are frequently examined through specific interventions or narrowly defined solution sets—such as particular retrofit techniques or housing typologies—rather than being structured as a comprehensive and explicit strategic decision space [33,76,77]. At the same time, although economic, environmental, and social aspects are increasingly considered, full integration of the three sustainability pillars within a unified assessment framework remains comparatively limited [78–81]. In addition, a persistent focus on technical and localized decision levels limits support for strategic reconstruction choices at neighborhood, urban, or regional

scales [75,82]. These observations indicate that existing studies provide valuable analytical components but rarely integrate reconstruction alternatives, sustainability indicators, and decision boundaries within a coherent methodological structure.

Moreover, a strong focus on technical performance and localized decision contexts, while essential for advancing reconstruction practice, leaves room for further development of sustainability-oriented frameworks capable of supporting strategic reconstruction planning across diverse post-earthquake environments [30,31,40,45,83,84], as illustrated in Figure 2.

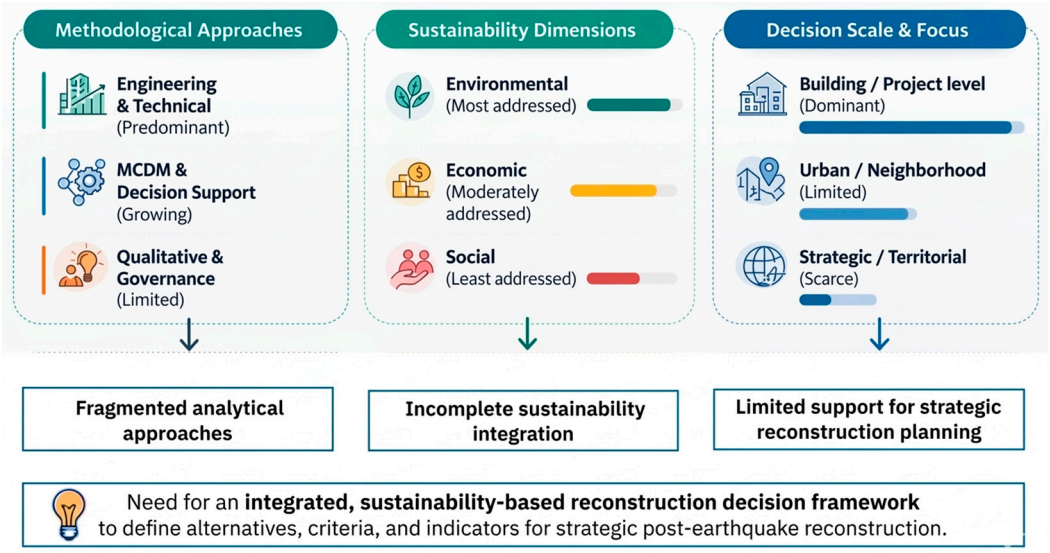


Figure 2. Summary of methodological patterns and research gaps identified in the reviewed literature on post-earthquake reconstruction.

Taken together, the reviewed literature highlights the need for a structured and transferable methodological framework capable of explicitly defining the reconstruction's alternative space; systematically adapting sustainability requirements, criteria, and indicators to post-earthquake conditions; and supporting transparent decision-making at the strategic reconstruction planning level. The following section introduces the methodological framework developed in this study to address these gaps.

3. Methodology

This study develops a context-adapted sustainability assessment model for post-earthquake reconstruction decisions by deriving an adaptation procedure from the canonical lifecycle of the Integrated Value Model for Sustainability Assessment (MIVES) [35,50,51,62,63,85–90]. MIVES is a multi-criteria decision-support methodology grounded in value engineering and multi-criteria decision analysis, structured around a hierarchical requirements tree (RT), the use of value functions to normalize heterogeneous indicators, and the aggregation of performance into a synthetic index to enable transparent comparison among alternatives [87].

MIVES is adopted as the reference methodology because its structure is particularly suited to reconstruction decision-making, where economic, environmental, and social criteria interact and are expressed through heterogeneous metrics [52]. Its value-function-based formulation allows consistent treatment of indicators expressed in different units [34], a critical requirement in construction sustainability assessments, and its extensive application in architecture [35] and civil engineering [88]—including disaster-related contexts—supports its suitability as a transferable methodological baseline [35,62,85,90]. At the same time, recent methodological developments in the MCDM field have explored the use of ensemble or

hybrid approaches that combine multiple decision-making methods to enhance robustness and ranking stability [91]. Likewise, guidance has been proposed for selecting context-appropriate MCDM techniques based on problem characteristics such as data uncertainty, computational complexity, and stakeholder diversity [92]. While such approaches may strengthen methodological robustness in data-rich and highly controlled environments, their implementation typically increases model complexity and computational burden. In post-earthquake reconstruction contexts—characterized by incomplete data, time pressure, and the need for transparent and transferable decision-support tools—maintaining methodological clarity and operational agility is essential. For this reason, the present study retains a single coherent MIVES-based structure, prioritizing interpretability, traceability, and practical applicability over methodological hybridization.

In its canonical form, the MIVES process is commonly presented as a staged workflow comprising: (1) definition of the problem, objectives, and system boundaries; (2) construction of the hierarchical requirements tree; (3) weighting of RT components; (4) definition of value functions; (5) definition and evaluation of alternatives and case studies; (6) calculation of the global sustainability index; and (7) model validation [34,35,51]. However, post-earthquake reconstruction is characterized by a highly heterogeneous decision space and by staged information availability, with many strategic decisions occurring before the detailed data required for weighting, value-function definition, and aggregation are available. In such contexts, it is methodologically appropriate to distinguish between conceptual model construction and operational model application [25,35].

Accordingly, the present article focuses on the conceptual adaptation stages required to construct a MIVES-based sustainability assessment model tailored to post-earthquake reconstruction. The relationship between the canonical MIVES lifecycle and the methodological steps developed in this study is illustrated in Figure 3. The figure clarifies which stages of the original MIVES methodology are addressed in the present research and how the proposed framework adapts these stages for the definition of reconstruction alternatives and sustainability indicators. It also summarizes the indicator adaptation process derived from the literature synthesis and the classification of reconstruction alternatives identified in the reviewed studies.

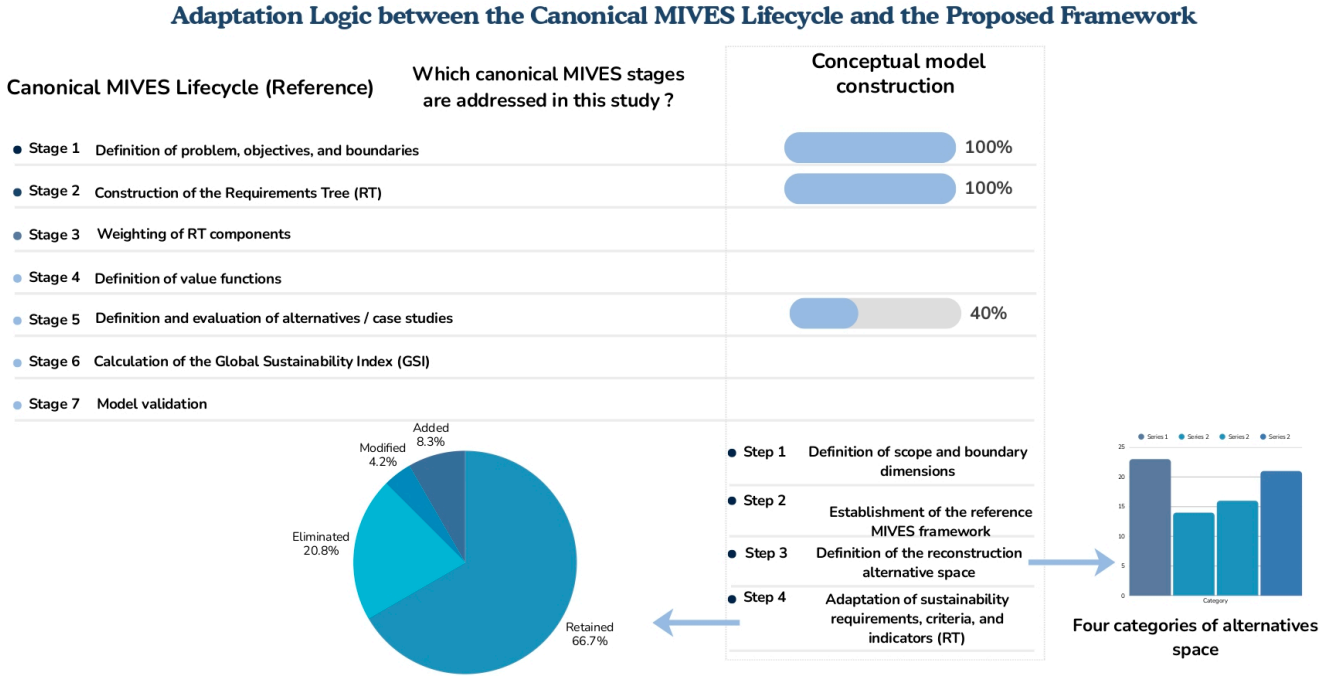


Figure 3. Adaptation logic between the canonical MIVES lifecycle and the proposed framework.

Within this framing, the methodology of Part I is organized into four adaptation steps derived from the early MIVES stages and from the need to explicitly structure the post-earthquake reconstruction decision space prior to indicator finalization: (Section 3.1) definition of scope and boundary dimensions; (Section 3.2) establishment of a reference MIVES framework; (Section 3.3) definition of the reconstruction alternative space; and (Section 3.4) adaptation of sustainability requirements, criteria, and indicators. The following subsections present these steps.

3.1. Definition of Scope and Boundary Dimensions

The first step of the adaptation methodology consists of defining the scope and boundary dimensions that condition the applicability of a sustainability assessment model for post-earthquake reconstruction. In MIVES-based decision-support systems, the definition of the problem, objectives, and boundaries is a prerequisite for constructing a coherent requirements tree and for ensuring consistency between the decision context, the reconstruction alternatives, and the sustainability indicators [34,51,52,86–88]. When adapting an existing MIVES framework to a new reconstruction context, this step is, therefore, required to determine which boundary dimensions must be explicitly defined before the model can be applied.

At this stage, the methodology does not assign specific boundary values; rather, it establishes the categories of boundaries that structure the adapted model during application. These boundary dimensions typically relate to the physical characteristics of the building stock, the nature and extent of damage, the functional role of buildings, the decision level at which reconstruction choices are made, and the phase of the reconstruction process being addressed. By explicitly identifying these boundary dimensions—without fixing their values—the methodology ensures that subsequent stages of framework adaptation remain configurable, internally consistent, and transferable across different post-earthquake reconstruction scenarios.

3.2. Establishment of the Reference MIVES Framework

The second step consists of establishing a reference MIVES framework that serves as the structural baseline for subsequent adaptation. This step does not involve selecting or applying a specific existing model; rather, it defines the procedure through which representative MIVES-based frameworks are identified and synthesized to inform the structure of the adapted assessment model. Establishing this reference baseline ensures methodological continuity with the MIVES lifecycle while avoiding arbitrary or isolated model construction.

The reference framework is derived through a focused literature collection of MIVES-based sustainability assessment studies relevant to reconstruction and post-event contexts. The search is conducted using the keyword “MIVES”, combined with contextual terms including “post-earthquake”, “post-disaster”, “post-conflict”, and “sustainability assessment”, in order to capture both earthquake-specific and closely related recovery scenarios. The search is limited to English-language, open-access journal articles published from 2015 onward, across three databases: Scopus [41], Web of Science [42], and Google Scholar [43], reflecting contemporary sustainability practices and recent methodological developments. The collected studies are analyzed to identify recurrent structural features of MIVES implementations—such as sustainability dimensions, hierarchical organization, and indicator structuring—which together constitute the reference framework to be adapted.

3.3. Definition of the Reconstruction Alternative Space

The third step of the adaptation methodology defines the reconstruction alternative space that the sustainability assessment model is intended to evaluate. This step is methodologically necessary because, within MIVES and related multi-criteria decision frameworks, sustainability indicators are meaningful only insofar as they are capable of discriminating against decision alternatives [93,94]. In post-earthquake reconstruction contexts, alternatives are highly heterogeneous in nature and scale, and their explicit definition therefore constitutes a prerequisite for any subsequent indicator adaptation [30,32,83,95–97].

At this stage, the methodology specifies how reconstruction alternatives are identified and structured, without selecting or parameterizing specific options. The alternative space is constructed at a typological level through a targeted review of post-earthquake and post-disaster reconstruction literature, focusing on permanent reconstruction strategies. Alternatives are organized according to their functional role in reconstruction decision-making, allowing the model to capture fundamentally different reconstruction pathways. Importantly, this step establishes the admissible set of alternative types from which case-specific reconstruction options will be selected and instantiated during the application phase (Part II). By defining the alternative space in advance, this step directly conditions both the formulation of sustainability indicators in Step 4 and the transparency of alternative selection in subsequent model application.

3.4. Adaptation of Sustainability Requirements, Criteria, and Indicators

The fourth step of the adaptation methodology addresses the adaptation of sustainability requirements, criteria, and indicators, corresponding to the construction of a requirements tree (RT) within the MIVES framework. In canonical MIVES applications, the RT represents the core structural element through which sustainability objectives are translated into an operable assessment model [35,50,51,62,63,85,88]. When adapting MIVES to post-earthquake reconstruction contexts, this step is, therefore, central, as it defines how sustainability is conceptually represented and structured in relation to the decision problem.

At this stage, the methodology specifies how indicators are adapted, rather than selecting or evaluating them. Sustainability indicators reported in the post-earthquake and post-disaster reconstruction literature are consolidated across economic, environmental, and social dimensions and examined in relation to the boundary dimensions identified in Step 1 and the reconstruction alternative space defined in Step 3. Indicator adaptation is carried out through retention, modification, elimination, or addition, ensuring that the resulting RT is recovery-oriented and capable of discriminating among alternative reconstruction pathways. The RT obtained through the application of this step constitutes the principal methodological output of the present article and is presented in the Results Section.

The methodological steps described in this section provide the analytical structure through which the MIVES framework is adapted to the specific context of post-earthquake reconstruction. Their application to the definition of reconstruction alternatives and sustainability indicators is presented in the following section.

4. Result

Section 4 presents the results obtained from applying the methodological procedure described in Section 3 to the context of post-earthquake reconstruction. Specifically, it introduces the reconstruction alternative space derived from the literature synthesis and the adapted requirements tree (RT) that structures the proposed sustainability assessment framework.

4.1. Definition of Scope and Boundary Dimensions

The application of Step 1 resulted in the explicit definition of the scope and boundary configuration of the adapted sustainability assessment model. The model is configured to support strategic decision-making in post-earthquake reconstruction, focusing on permanent reconstruction choices rather than emergency response or temporary shelter solutions. It is positioned at the pre-design planning level, where alternative reconstruction pathways are compared prior to detailed structural design or technical optimization. The application of the model is explicitly intended to occur after the completion of structural safety assessment and damage diagnosis, which are treated as external prerequisites and are therefore excluded from the sustainability assessment itself.

The adapted model is defined for reinforced concrete (RC) buildings as a reference structural typology, given their material intensity and the wide spectrum of feasible reconstruction interventions they admit. This provides a technically robust basis for structuring and differentiating strategic reconstruction alternatives within the sustainability framework. The use of reinforced concrete buildings, therefore, reflects a defined methodological boundary for model development rather than an assumption of structural homogeneity across post-earthquake building stocks. In practice, reconstruction planning frequently involves heterogeneous structural systems (e.g., masonry, timber, or mixed construction), and the framework developed in this study is intended primarily for application within RC-dominated urban contexts where comparable intervention pathways can be systematically evaluated. The scope of application is not restricted by building function, allowing use for residential, public, or mixed-use buildings. With respect to damage conditions, the model addresses earthquake-damaged buildings deemed structurally assessable for reconstruction intervention, without imposing a fixed damage threshold within the sustainability assessment. Temporally, the model is intended for use during the reconstruction planning phase, following emergency actions and structural evaluation and preceding long-term operation and maintenance considerations. This boundary configuration establishes a coherent and transferable decision context that conditions the subsequent definition of the reference framework, reconstruction alternative space, and requirements tree.

4.2. Reference MIVES Framework Adopted for Model Adaptation

The application of Step 2 resulted in the identification of seven MIVES-based sustainability assessment studies relevant to post-earthquake, post-disaster, and post-conflict reconstruction contexts. These studies were selected through the application of the search criteria defined in Section 3.2 and constitute the empirical basis for establishing the reference MIVES framework used in the present research.

The selected studies and their main characteristics are reported in Table 2, including the event or context addressed, the object of assessment, the type of alternatives evaluated, and the methodological contribution of each study. As shown in the table, the identified applications of MIVES span a range of post-event contexts, including post-disaster temporary housing, post-earthquake reconstruction techniques, seismic and energetic retrofit solutions, structural risk assessment, and post-conflict reconstruction of reinforced concrete buildings. Collectively, these studies document the structural configurations and assessment logics through which MIVES have been operationalized in recovery-related decision problems. The synthesis of these applications defines the reference MIVES framework adopted in this study and provides the structural basis for the definition of the reconstruction of alternative space and the adaptation of sustainability requirements, criteria, and indicators presented in the following sections.

Table 2. MIVES-based sustainability assessment studies informing the reference framework for post-event reconstruction contexts.

Authors	Post-Event Context	Assessment Scale	Decision Problem Addressed	Methodological Role of MIVES
Hosseini et al. (2016) [34]	Post-earthquake (Bam, Iran)	Building system	Evaluation of temporary housing technologies	Standalone multi-criteria sustainability assessment framework, where MIVES functions as the primary tool for evaluating alternative solutions
Hosseini et al. (2018) [51]	Post-disaster	Site level	Spatial selection of temporary housing locations	Embedded evaluation module within an optimization-based decision system, where MIVES supports the assessment of alternatives generated through algorithmic processes
Cárdenas-Gómez et al. (2021) [38]	Post-earthquake	Building technique	Comparison of reinforced reconstruction techniques	Comparative sustainability assessment tool for predefined construction alternatives, applied to evaluate and rank technical solutions
Hosseini et al. (2022) [35]	Post-disaster (Tehran, Iran)	Site level	Constrained site selection for temporary housing	Hybrid decision-support framework integrating MIVES with GIS and optimization models, enabling spatially constrained and multi-criteria site selection
Cerracchio et al. (2025) [33]	Seismic vulnerability & retrofit	Building level	Evaluation of seismic–energetic retrofit solutions	Integrated sustainability and performance assessment framework, combining MIVES with structural and energy performance evaluation
Rezk et al. (2025) [52]	Post-conflict (blast damage)	Building level	Strategic selection among reconstruction alternatives	Strategic decision-support framework combining MIVES with Delphi-based expert weighting, enabling evaluation of reconstruction alternatives under uncertainty

4.3. Role-Based Classification of Studies Informing the Reconstruction Alternative Space

Following the establishment of the reference MIVES framework in Section 4.2 and the synthesis of the state-of-the-art literature, the reviewed studies were examined to structure and delimit the post-earthquake reconstruction alternative space addressed by the adapted model. Rather than providing an additional literature review, this step organizes the reviewed studies according to their role in informing the construction of the reconstruction alternative space within the proposed framework. Based on this analysis, four distinct roles of contribution were identified, reflecting different ways in which the literature frames recovery objectives, constrains decision-making conditions, or explicitly formulates reconstruction alternatives. This classification, therefore, functions as the analytical mechanism through which the reconstruction alternative space is defined in Step 3 of the adaptation methodology.

The four categories identified, together with their definitions, representative keywords, and the number of studies assigned to each category, are summarized in Table 3. To avoid repetition within the main text, the detailed classification of all reviewed studies is provided in Appendix A.

Table 3. Role-based classification of reviewed studies informing the reconstruction alternative space.

Study Category	Definition	Representative Keywords	Number of Studies
Strategic recovery framing studies	Studies that define overarching recovery objectives, performance targets, and normative orientations for post-earthquake reconstruction without formulating explicit reconstruction schemes	Functional recovery, resilience, sustainability goals, build back better, long-term recovery, circular economy	23
Decision drivers and constraint studies	Studies that analyze institutional, economic, regulatory, and social conditions shaping reconstruction decisions, without framing reconstruction as a choice among alternatives	Governance, regulation, financing, prioritization, social acceptance, participation, feasibility	19
Intervention- or scheme-oriented studies	Studies that explicitly formulate post-earthquake reconstruction as a choice among distinguishable intervention schemes at building or strategic level	Repair, strengthening, retrofit, demolition and reconstruction, relocation, reconstruction strategy	10
Out-of-scope reconstruction-related studies	Studies addressing post-disaster contexts that do not contribute directly to permanent building reconstruction decisions	Emergency response, temporary housing, damage assessment, hazard analysis	21

The classification of studies was conducted through a qualitative coding process based on the primary decision focus of each study, as explicitly stated in its objectives and methodological approach. In cases where studies addressed multiple aspects (e.g., decision drivers while implicitly referring to reconstruction alternatives), classification was assigned according to the dominant analytical contribution. Studies were categorized as intervention- or scheme-oriented only when reconstruction was explicitly formulated as a choice among distinguishable alternative pathways. This approach ensures conceptual consistency between categories while acknowledging partial overlaps between research themes.

Among the four identified categories, intervention- or scheme-oriented studies (Category 3) were selected as the direct empirical basis for defining the reconstruction alternative space addressed by the adapted sustainability assessment model. These studies explicitly formulate post-disaster reconstruction as a choice among distinguishable intervention schemes, whether at building or settlement level.

To ensure transparency in the derivation of the alternative space, the intervention-oriented studies retained within the boundary conditions of post-war, post-conflict, post-disaster, or post-earthquake contexts are summarized in Table 4. The table documents the hazard context, the reconstruction alternatives compared, and the methodological approach.

Table 4. Intervention-oriented studies (Category 3) informing the strategic reconstruction alternative space.

Study	Hazard Context	Reconstruction Alternatives Compared	Method
[64]	Post-flood	Emergency strengthening schemes (RC jacketing, steel bracing, localized reinforcement, stabilization options)	Prospect Theory prioritization
[38]	Post-earthquake	Traditional vs. reinforced adobe reconstruction techniques	MIVES
[33]	Seismic	Seismic–energetic retrofit packages combining structural strengthening and energy upgrades	MIVES
[52]	Post-war	Refurbishment; Strengthening; Demolition & reconstruction; Preservation	MIVES–Delphi
[36]	Post-disaster	Optimization-generated reconstruction design configurations	Multi-objective optimization
[73]	Post-earthquake	Three rural settlement reconstruction approaches	Comparative evaluation
[72]	Post-earthquake	Two rural settlement reconstruction approaches	Comparative case study
[26]	Seismic	Alternative seismic retrofit techniques for strategic RC buildings	Resilience-based evaluation
[47,49]	Post-war	Alternative residential reconstruction strategies evaluated under sustainability and risk criteria	Multi-criteria sustainability risk model

The intervention-oriented literature exhibits substantial heterogeneity in both scale and decision level. Some studies compare technical retrofit or strengthening solutions within a single intervention category (e.g., Li et al. [64]; Vona et al. [26]; Cerracchio et al. [33]; Cárdenas-Gómez et al. [38]). Others employ optimization-based reconstruction design frameworks (Izadinia et al., 2023 [36]). A smaller subset formulates reconstruction as a strategic choice among fundamentally different pathways, such as repair, strengthening, demolition and reconstruction (Rezk et al. [52]; Khaddour et al. [47,49]). Additional studies operate at the settlement level, comparing governance or development approaches in post-earthquake contexts (Yang et al. [73]; Peng [72]).

This diversity confirms that reconstruction alternatives are defined differently across the literature and depend on scale, governance structure, hazard context, and methodological framing. Consequently, the reconstruction's alternative space adopted in this study is derived through explicit alignment with the decision boundaries defined in Section 4.1.

4.4. Adapted Sustainability Requirements Tree for Post-Earthquake Reconstruction

The application of Step 4 resulted in the construction of an adapted sustainability requirements tree (RT) for post-earthquake reconstruction at the strategic decision level. The development of this RT builds on the literature review presented in the State-of-the-Art Section, Table 2 and Appendix A, where sustainability indicators used in post-earthquake and post-disaster reconstruction studies were identified and documented.

To ensure methodological consistency between the extracted indicators and the operational scope of the proposed model, the consolidation process was structured in two sequential stages. First, the indicators were examined through a scale-based analytical classification to determine how sustainability dimensions are distributed across different intervention levels. This step enables identification of scale-dependent patterns in indicator selection and clarifies the relevance of each group to building-level strategic decisions.

The results of this classification are presented in Section 4.4.1. Based on this structured mapping, a selection and adaptation process was then conducted to define the final indicator configuration applicable to the strategic building-level assessment model. This second stage, detailed in Section 4.4.2, documents the retention, modification, elimination, and addition of indicators leading to the final adapted requirements tree.

4.4.1. Scale-Based Classification of Sustainability Indicators

In order to structure the consolidation of sustainability indicators, the reviewed post-disaster and post-earthquake reconstruction studies were classified according to their primary intervention scale. This classification serves an analytical role in the development of the framework by identifying how sustainability indicators vary depending on the level at which reconstruction decisions are formulated. Four intervention scales were identified in the reviewed literature: building-level reconstruction, site-level reconstruction, community/settlement-level reconstruction, and urban/infrastructure-level reconstruction.

For each scale, indicators were grouped according to sustainability pillar and further characterized by their decision horizon activation, indicator role, and classification as core or context-specific variables. Decision horizon activation indicates the stage of the reconstruction process in which an indicator becomes relevant (emergency, transitional, or long-term). Indicator role defines its function within the assessment, distinguishing variables that directly influence the evaluation of reconstruction alternatives from those that provide supporting or complementary information. Core indicators are consistently applicable across reconstruction scenarios within the defined decision boundary, whereas context-specific indicators are activated only under particular local, economic, or institutional conditions.

(a) Building-Level Reconstruction Studies

Building-level reconstruction studies address direct interventions on damaged or existing buildings, including repair, retrofitting, demolition and reconstruction, and temporary housing configurations. At this scale, sustainability assessment is primarily performance-based and enables comparison among alternative technical strategies. The sustainability indicators identified in the reviewed building-level studies are summarized in Table 5.

At the building scale, environmental indicators related to embodied impacts and resource use appear consistently across studies. Economic cost indicators are present in most comparative assessments, while recovery time and functional reoccupancy are emphasized in emergency-oriented contexts. These indicators form the primary reference pool for the strategic reconstruction model developed in this study.

(b) Site-Level Reconstruction Studies

Site-level reconstruction studies address spatial decision-making related to land suitability, hazard exposure, relocation planning, and infrastructure readiness. At this scale, sustainability assessment is predominantly location-oriented and strongly influenced by risk conditions and accessibility considerations. The sustainability indicators identified in site-level reconstruction studies are presented in Table 6.

At the site scale, sustainability indicators are primarily associated with spatial risk mitigation and service accessibility. Hazard exposure distance, land suitability, and infrastructure availability recur across site-selection models and constitute the core environmental and economic parameters. These indicators are considered analytically but are not directly incorporated into the building-level reconstruction framework.

Table 5. Sustainability indicators in building-level reconstruction studies.

Indicators	Sustainability Pillar	Decision Horizon Activation	Indicator Role	Core/Context-Specific	References
Initial reconstruction costs	Economic	All horizons	Strategic	Core	[34,35,85,98,99]
Cost per m^2	Economic	All horizons	Operational	Core	[8,47,49,52,100–103]
Long-term maintenance costs	Economic	Long-term	Strategic	Core	[62,102,104]
Demolition costs	Economic	All horizons	Strategic	Core	[60,85,105]
Reconstruction process duration	Economic	Emergency/Transitional	Operational	Context-activated	[70,102,106]
Demolition time	Economic	Emergency	Operational	Context-activated	[81,107]
Property-added value	Economic	Long-term	Strategic	Context-activated	[31,60,108,109]
Recovery time/downtime (time to functional recovery)	Economic	Emergency/Transitional	Strategic	Core	[52,110]
Embodied CO_2	Environmental	Long-term	Strategic	Core	[34,35,51,52,105,111–113]
Operational CO_2 emissions	Environmental	Long-term	Strategic	Core	[34,35,51,52,105,111–113]
Percentage of rubble waste	Environmental	Long-term	Operational	Core	[61,101,114]
Embodied energy	Environmental	Long-term	Strategic	Core	[100,112,115–117]
Use of recycled/local	Environmental	Long-term	Strategic	Context-activated	[39–119]
Material consumption	Environmental	Long-term	Strategic	Core	[77–121]
Building historical significance	Social	Context-dependent	Strategic	Context-activated	[52]
Architectural preservation	Social	Context-dependent	Strategic	Context-activated	[70]
Building importance	Social	Context-dependent	Strategic	Context-activated	[52]
Worker safety	Social	All horizons	Operational	Core	[91,102]
Community health and safety	Social	All horizons	Strategic	Core	[56,122–124]
Community engagement	Social	All horizons	Strategic	Core	[45,125,126]
Noise pollution	Social	All horizons	Operational	Context-activated	[127]
Other inconveniences (disturbance, access disruption	Social	All horizons	Operational	Context-activated	[52]
Ease of implementation	Social	All horizons	Strategic	Core	[38]
Knowledge and Implementation	Social	All horizons	Strategic	Core	[38]

(c) Community/Settlement-Level Studies

Community- and settlement-level reconstruction studies examine recovery processes beyond individual buildings or sites, focusing on collective resilience, governance capacity, and socio-economic stability. At this scale, sustainability assessment shifts from technical performance to institutional and social dynamics influencing long-term recovery. The corresponding sustainability indicators are summarized in Table 7.

Table 6. Sustainability indicators in site-level reconstruction studies.

Indicator	Sustainability Pillar	Decision Horizon Activation	Indicator Role	Core/Context-Specific	References
Distance from hazard zones	Environmental	Emergency	Strategic	Core	[34,35,51,104]
Land suitability/soil stability	Environmental	All horizons	Strategic	Core	[34,51,95,104]
Environmental compatibility of site	Environmental	Long-term	Strategic	Context-activated	[34,35,51,95,104]
Infrastructure availability	Economic	Emergency	Strategic	Core	[104]
Site preparation cost	Economic	All horizons	Operational	Core	[34,35,51,104]
Population density compatibility	Social	Transitional	Strategic	Context-activated	[104]
Social integration potential	Social	Long-term	Strategic	Context-activated	[34,35,104]
Urban–rural connectivity	Economic/Social	Long-term	Strategic	Context-activated	[104]
Accessibility to public services	Social	Emergency/transitional	Strategic	Core	[82]

Table 7. Sustainability indicators in community/settlement-level reconstruction studies.

Indicator	Sustainability Pillar	Decision Horizon Activation	Indicator Role	Core/Context-Specific	References
Livelihood restoration	Economic	Transitional	Strategic	Core	[55,67,75]
Housing affordability	Economic	Long-term	Strategic	Core	[96]
Stakeholder coordination capacity	Governance	All horizons	Strategic	Core	[68,72,73]
Governance efficiency	Governance	All horizons	Strategic	Core	[113]
Community participation in planning and design	Social	All horizons	Strategic	Core	[64,76]
Institutional trust	Social	Transitional/long-term	Strategic	Context-activated	[74]
Equity in resource distribution	Social	Transitional	Strategic	Context-activated	[60,96]
Social cohesion	Social	Long-term	Strategic	Core	[56,58]
Risk perception and acceptance	Social	Emergency/transitional	Strategic	Context-activated	[76,109]
Functional continuity of services	Social	Emergency/transitional	Strategic	Context-activated	[109]

At the community and settlement scale, sustainability indicators are predominantly socio-economic and governance-oriented. Participation, coordination, livelihood restora-

tion, and institutional capacity recur across contexts and represent core elements of recovery-oriented sustainability. While relevant for broader recovery planning, these indicators fall outside the direct decision boundary of the building-level model developed in this study.

(d) Urban/Infrastructure-Level Studies

Urban- and infrastructure-level reconstruction studies address sustainability from a systemic perspective, focusing on large-scale recovery strategies, infrastructure networks, and long-term territorial transformation. At this scale, indicators extend beyond project-based metrics and emphasize system performance, governance capacity, and strategic investment pathways. The sustainability indicators identified at this scale are reported in Table 8.

Table 8. Sustainability indicators in urban/infrastructure-level reconstruction studies.

Indicator	Sustainability Pillar	Decision Horizon Activation	Indicator Role	Core/Context-Specific	References
Decarbonization trajectory	Environmental	Long-term	Strategic	Core	[100]
Renewable energy share	Environmental	Long-term	Strategic	Core	[100]
Energy security/supply reliability	Environmental/ Governance	Long-term	Strategic	Context-activated	[100]
Ecosystem restoration (soil, water, biodiversity)	Environmental	Long-term	Strategic	Context-activated	[97]
Circular material flows/reuse rate	Environmental	Long-term	Strategic	Context-activated	[99,101]
Waste recovery systems	Environmental	Long-term	Strategic	Context-activated	[61,99]
Reconstruction financing mechanisms	Economic	Transitional/long-term	Strategic	Core	[74]
Investment allocation efficiency	Economic	Long-term	Strategic	Core	[81]
Urban–rural connectivity	Economic/Social	Long-term	Strategic	Context-activated	[82]
Strategic governance coordination	Governance	All horizons	Strategic	Core	[81,96]

At the urban and infrastructure scale, sustainability indicators expand toward system-level environmental performance, strategic economic capacity, and governance coordination. These indicators characterize macro-scale recovery processes but are not directly transferable to building-level reconstruction decisions without boundary reformulation.

4.4.2. Indicator Selection and Strategic Adaptation

Following the consolidation of the sustainability indicator universe across the four intervention scales (Tables 5–8), a selection process was conducted to define the indicator set applicable to the strategic building-level reconstruction model.

Given that the proposed assessment framework operates at the building strategic decision level, the primary extraction basis was the building-level indicator group (Table 5).

Indicators identified exclusively at site, community, or urban scales were not directly transferred unless their operational meaning could be reformulated to reflect building-level strategic relevance.

The selection and adaptation process was guided by four alignment criteria: boundary consistency with the strategic building-level scope defined in Section 4.1, relevance to post-earthquake reconstruction decision-making rather than prioritization or territorial planning, non-redundancy with other retained indicators, and the ability to discriminate meaningfully among alternative reconstruction pathways defined in Section 4.3. In addition, the process examined the recurrence of indicators across the reviewed studies and their conceptual relevance to the defined decision boundary. Indicators repeatedly employed in reconstruction-oriented assessments were retained as core components of the framework, while indicators associated with other intervention scales were excluded when their operational meaning could not be consistently reformulated at the building strategic level. Where multiple indicators represented closely related conceptual dimensions, consolidation or reformulation was applied to avoid redundancy while preserving the underlying sustainability objective.

Each indicator from the building-level group was, therefore, examined and classified as retained (in orange), modified (in green), eliminated (in blue), or added (in gray). The outcomes of this systematic adaptation process are presented in Table 9.

Table 9. Adaptation outcomes of sustainability indicators extracted from the literature for strategic post-earthquake reconstruction assessment.

I#	Indicators	Indicator Meaning at Strategic Level	Adaptation Decision	Clarified Rationale
I1	Initial reconstruction costs	Total absolute cost required to implement a reconstruction strategy for a given building	Retained	Represents the aggregate financial requirement of each reconstruction alternative and enables direct comparison at the strategic decision level
I2	Cost per m^2	Normalized reconstruction cost per unit area	Retained	Allows for comparability across buildings of different sizes and damage conditions by standardizing cost intensity
I3	Long-term maintenance costs	Cost associated with maintaining the building after reconstruction	Retained	Captures lifecycle economic implications beyond initial investment, consistent with long-term sustainability assessment
I4	Demolition costs	Cost associated with demolition activities	Retained	Necessary to differentiate reconstruction pathways involving partial or total demolition from rehabilitation-based strategies
I5	Reconstruction process duration	Time required to complete construction activities	Eliminated	Integrated within recovery time to avoid redundancy; not treated as an independent strategic indicator
I6	Demolition time	Time required to complete demolition works	Eliminated	Considered a subprocess of overall recovery performance and not independently discriminative at the strategic level

Table 9. *Cont.*

I#	Indicators	Indicator Meaning at Strategic Level	Adaptation Decision	Clarified Rationale
I7	Recovery time/downtime (time to functional recovery)	Time required to restore functional usability of the building	Retained	Core recovery-oriented indicator reflecting the combined temporal performance of reconstruction strategies
I8	Property-added value	Increase in market or asset value after reconstruction	Eliminated	Classified as context-dependent; activation depends on specific economic or market conditions and therefore not retained as a core indicator for baseline comparison
I9	Embodied CO_2	Carbon emissions associated with reconstruction materials and processes	Retained	Widely recognized lifecycle environmental indicator capturing the environmental impact of reconstruction activities
I10	Operational CO_2 emissions	Widely adopted indicator reflecting environmental impact of reconstruction strategies	Retained	Reflects long-term environmental performance and complements embodied impact assessment
I11	Percentage of rubble waste	Quantity of waste generated by demolition and reconstruction	Retained	Critical for distinguishing demolition-intensive strategies and assessing waste-related environmental impacts
I12	Embodied energy	Energy consumed in producing and assembling reconstruction materials	Retained	Retained as complementary to embodied CO_2 to capture energy-related environmental impacts without redundancy
I13	Use of recycled/local materials	Degree of use of recycled or locally sourced materials	Retained	Reflects circular economic principles and resource efficiency in reconstruction processes
I14	Material consumption	Quantity of materials required for reconstruction	Retained	Captures resource intensity and supports evaluation of material efficiency across alternatives
I15	Building historical significance	Cultural or historical value of the building	Eliminated	Considered context-activated; primarily relevant in heritage-sensitive reconstruction contexts and not universally applicable to the defined decision boundary
I16	Architectural preservation	Architectural value related to preservation objectives	Eliminated	Overlaps with heritage-specific evaluation domains and therefore excluded from the generalized building-level sustainability framework
I17	Building importance	Strategic or functional importance of the building	Eliminated	Highly dependent on external prioritization frameworks and not directly linked to intrinsic sustainability performance of alternatives

Table 9. *Cont.*

I#	Indicators	Indicator Meaning at Strategic Level	Adaptation Decision	Clarified Rationale
I18	Worker safety	Safety risks to construction workers during reconstruction	Retained	Core social sustainability indicator reflecting occupational risk conditions during reconstruction processes
I19	Community health and safety	Health and safety impacts on surrounding community during works	Modified	Reframed to reflect construction-phase exposure and localized impacts rather than emergency-response conditions
I20	Community engagement	Degree of stakeholder and community participation	Added	Introduced to capture governance-related and participatory dimensions of reconstruction decision-making
I21	Noise pollution	Noise impacts generated during reconstruction activities	Retained	Represents a measurable and recurrent form of social disturbance in urban reconstruction contexts
I22	Other inconveniences (disturbance, access disruption	Disturbance, such as access disruption and daily-life interference	Retained	Captures broader indirect social impacts not represented by single disturbance indicators
I23	Ease of implementation	Practical ease of executing the reconstruction strategy	Retained	Reflects constructability and logistical feasibility under post-earthquake conditions
I24	Knowledge and Implementation	Availability of technical knowledge and expertise	Retained	Influences feasibility, risk, and reliability of strategy execution
I25	Functional usability/reoccupancy	Ability to reoccupy and use the building after reconstruction	Added	Central indicator of functional recovery and alignment with reconstruction objectives

The outcome of this process is a fixed and context-adapted MIVES requirements tree, structured hierarchically across sustainability dimensions, criteria, and indicators. This RT represents the principal result of the present article and defines the structural backbone of the proposed sustainability assessment model. The complete adapted requirements tree is illustrated in Figure 4, which synthesizes the final configuration of the model.

The resulting requirements tree (RT) structures the sustainability assessment model into three principal dimensions: economic (R1, shown in blue), environmental (R2, shown in green), and social (R3, shown in orange). Each dimension is further organized into criteria representing key evaluation domains relevant to strategic reconstruction decision-making. Within the Economic dimension, the criteria cost (C1) and recovery performance (C2) address the financial implications and recovery timelines associated with alternative reconstruction pathways. The Environmental dimension includes the criteria Emissions (C3), waste generation (C4), energy demand (C5), and material resource consumption (C6), reflecting key lifecycle environmental impacts related to reconstruction activities. The social dimension comprises community impact (C7), construction process impacts (C8), technical feasibility (C9), and functional usability (C10), capturing the broader societal and operational implications of reconstruction decisions. Each criterion is operationalized through a set of indicators derived from the structured literature synthesis and adapted to the strategic building-level decision boundary of the proposed framework. This hierarchical

organization improves transparency in how sustainability considerations are translated into measurable evaluation components for comparing reconstruction alternatives and establishes the complete structural configuration required to proceed to the application phase of the proposed framework, as indicated in the Abstract.

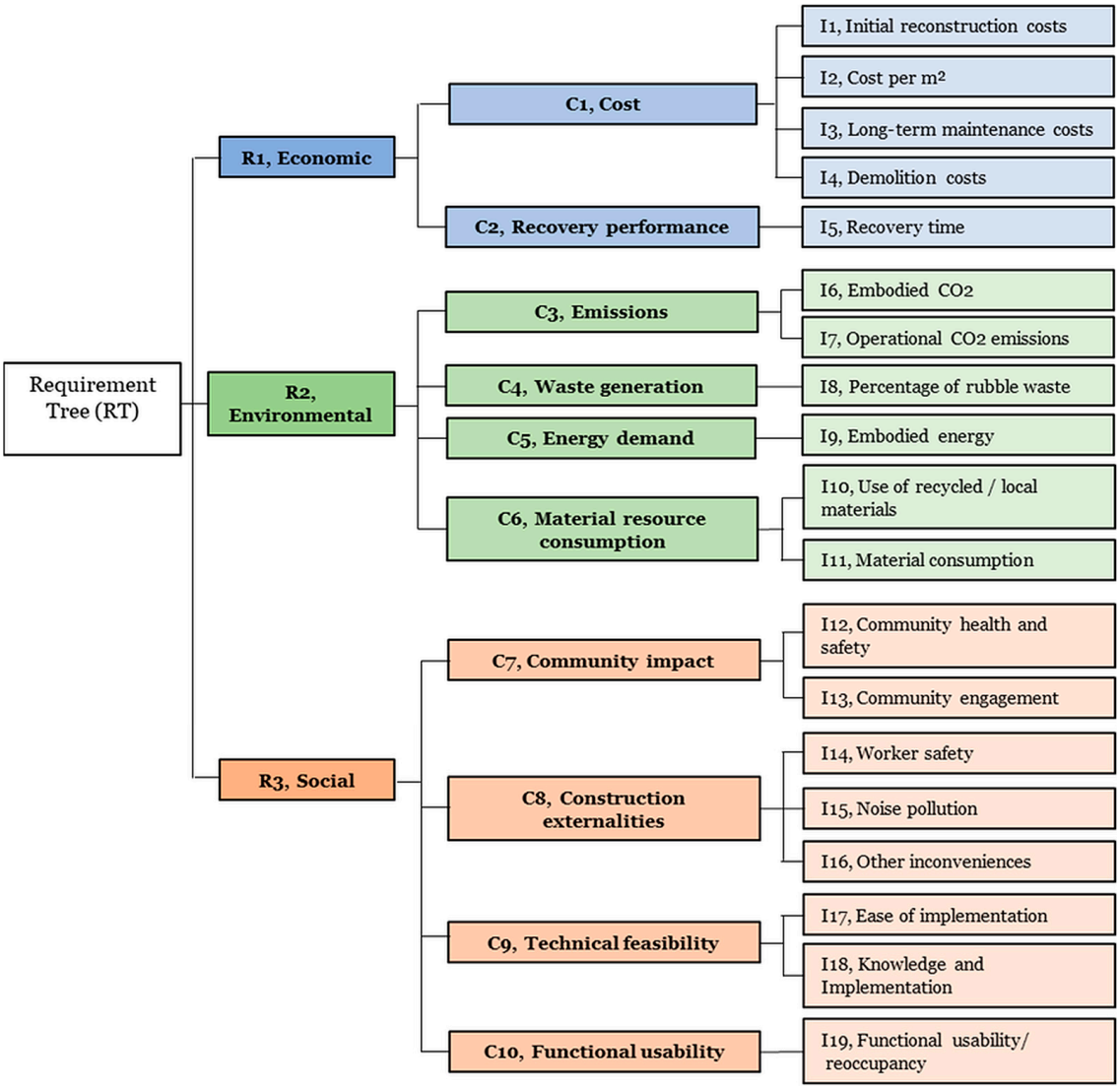


Figure 4. Adapted MIVES requirements tree (RT) for sustainability assessment of post-earthquake reconstruction alternatives at the strategic decision level.

5. Discussion

The scale-based classification highlights that sustainability indicators used in reconstruction studies are strongly dependent on the level of intervention considered. While building-level assessments prioritize technical performance, cost, and recovery time, broader community and urban studies introduce governance, resilience, and territorial dimensions. This heterogeneity indicates that indicator configurations cannot be directly transferred across scales without methodological adjustment. Within this context, the present study does not seek to validate the effectiveness of the MIVES methodology itself but to demonstrate how its hierarchical structure can be systematically adapted to a clearly defined strategic building-level decision scope. In contrast to existing MIVES-based applications, which typically adopt predefined decision contexts and indicator sets, the present study explicitly addresses the prior methodological step of structuring the decision

framework itself, including the definition of reconstruction alternatives and the adaptation of indicators in relation to a clearly defined decision boundary.

The comparative examination of MIVES-based applications confirms that indicator selection consistently reflects the decision boundaries and recovery objectives of each context. Early post-disaster applications (Hosseini et al., 2016) [34] conceptualize economic performance primarily through public expenditure and maintenance indicators in temporary housing assessment, consistent with emergency deployment objectives. Site-selection models (Hosseini et al., 2018; 2022) [35,51] extend this logic to include land price, site preparation cost, and service accessibility, aligning economic evaluation with spatial and logistical decision boundaries. Reconstruction and retrofit-oriented studies adopt different economic emphases: Cárdenas-Gómez et al. (2021) [38] prioritize constructability and material accessibility, Cerracchio et al. (2025) [33] focus on investment cost and expected losses, and Rezk et al. (2025) [52] incorporate cost per square meter and property-added value within a post-conflict reconstruction framework. These variations reflect differences in decision scope rather than methodological inconsistency. However, these studies generally operate with implicitly defined or case-specific reconstruction alternatives, without formally structuring the alternative space as a distinct methodological step.

A comparable pattern emerges in the environmental dimension. Temporary housing models (Hosseini et al., 2016) [34] emphasize land-use disturbance and short-term construction impacts, while site-selection studies (Hosseini et al., 2018; 2022) [35,51] integrate ecosystem and location-dependent emissions. Reconstruction-focused applications (Cárdenas-Gómez et al., 2021; Cerracchio et al., 2025) [33,38] expand environmental evaluation to embodied carbon and operational performance, and Rezk et al. (2025) [52] explicitly incorporate embodied CO_2, operational CO_2, and demolition waste. Environmental indicator configurations, therefore, correspond to the permanence and technical depth of the intervention considered. This confirms that environmental indicators are selected in response to intervention characteristics but are rarely derived through an explicit, scale-consistent adaptation process linked to a predefined strategic decision boundary.

The most pronounced variation is observed in the social dimension. Hosseini et al. (2016) [34] frame social performance through minimum living standards and health, whereas Hosseini et al. (2018, 2022) [35,51] emphasize accessibility and safety in site-level decisions. Technical retrofit studies (Cárdenas-Gómez et al., 2021; Cerracchio et al., 2025) [33,38] focus primarily on occupational safety and construction disturbance. Rezk et al. (2025) [52] extend social assessment to cultural significance and participation within post-conflict reconstruction. These differences reflect varying social objectives—emergency, adequacy, feasibility, territorial integration, or cultural continuity—across reconstruction contexts. Across these applications, social indicators are adapted to context-specific objectives, yet their integration within a unified and explicitly bounded decision framework remains limited.

Beyond indicator configurations, the role-based classification of reconstruction studies further clarifies how reconstruction is conceptualized in the literature. While strategic recovery framing studies define overarching objectives, and decision-driver studies examine institutional or socio-economic constraints, only intervention- or scheme-oriented studies explicitly formulate reconstruction as a choice among distinguishable alternative pathways. By selecting this latter category as the operative basis for the alternative space, the present study anchors sustainability assessment within a clearly defined strategic decision context. This distinction ensures that the adapted requirements tree is aligned not only with sustainability dimensions but also with the structural logic of alternative comparison at the planning stage. This explicit construction of the reconstruction alternative space represents

a key methodological distinction from previous MIVES applications, where alternatives are typically assumed rather than systematically defined.

Against this background, the present study contributes by formalizing a structured alignment process between sustainability indicators and a predefined strategic building-level reconstruction boundary. Rather than proposing new sustainability dimensions, it systematizes the selection, reformulation, and consolidation of recurrent indicators to ensure coherence with recovery-oriented objectives and heterogeneous reconstruction alternatives. The resulting requirements tree, therefore, represents a context-consistent configuration derived from existing MIVES applications but explicitly anchored to post-earthquake strategic decision-making. In this sense, the contribution of the study lies not in redefining MIVES itself but in extending its application through the formalization of the decision framework required for its consistent use in reconstruction planning.

This discussion confirms that MIVES-based sustainability assessment is structurally adaptable across emergencies, site-selection, retrofit, post-conflict, and reconstruction contexts. At the same time, it demonstrates that explicit articulation of decision boundaries is essential to maintain consistency between sustainability indicators and reconstruction objectives. The principal contribution of this article lies in formalizing this boundary–indicator alignment for strategic post-earthquake building-level reconstruction, providing a transparent methodological foundation for subsequent model operationalization and empirical application. By explicitly linking decision boundaries, reconstruction alternatives, and sustainability indicators within a unified structure, the proposed framework advances the methodological rigor of MIVES-based decision-support applications in post-earthquake reconstruction contexts.

6. Conclusions

This study clarifies that sustainability assessment in post-earthquake reconstruction must be explicitly conditioned by the scale of intervention and the decision boundary within which reconstruction choices are framed. Reconstruction alternatives and sustainability indicators cannot be coherently transferred across contexts without structured alignment between the defined strategic scope and the assessment configuration.

The principal contribution of this article lies in formalizing a transparent, literature-grounded derivation process that links reconstruction alternative structuring and indicator configuration within a MIVES-based framework. Through the role-based classification of existing studies, the reconstruction alternative space was first explicitly delimited at the strategic building level, and sustainability indicators were subsequently consolidated and adapted according to this boundary. This sequential boundary–alternative–indicator alignment establishes a reproducible methodological pathway rather than relying on predefined assessment templates.

The resulting adapted requirements tree, comprising 10 criteria and 19 indicators organized across the sustainability dimensions, constitutes a context-consistent hierarchical structure derived from existing post-earthquake and post-disaster research. By making explicit how alternative spaces and indicator sets should be constructed in relation to clearly defined decision boundaries, this study strengthens methodological rigor in sustainability-oriented reconstruction planning and enhances conceptual clarity in strategic decision-support for reinforced concrete buildings in seismic contexts.

Future research will proceed with the remaining stages of the canonical MIVES life-cycle, including weighting of the requirements tree components through expert-based procedures, definition of value functions for normalization of heterogeneous metrics, aggregation into a composite sustainability index, and empirical application to real post-earthquake reconstruction case studies. These stages will operationalize and validate

the framework across varying governance conditions, resource constraints, and damage scenarios, completing the full methodological implementation initiated in this study.

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Appendix A

Table A1. Role-based classification of reviewed studies in post-earthquake reconstruction decision-making.

References	Strategic Recovery Framing	Decision Drivers and Constraints	Intervention- or Scheme-Oriented	Out-of-Scope Reconstruction-Related
[128]	✓			
[109]	✓			
[40]		✓		
[129]		✓		
[64]			✓	
[130]		✓		
[35]				✓
[34]				✓
[38]			✓	
[51]				✓
[85]		✓		
[33]			✓	
[52]			✓	
[37]				✓
[74]		✓		
[131]		✓		
[99]	✓			
[132]		✓		
[100]				✓
[96]		✓		
[97]				✓
[133]				✓
[36]			✓	
[31]	✓			

Table A1. *Cont.*

References	Strategic Recovery Framing	Decision Drivers and Constraints	Intervention- or Scheme-Oriented	Out-of-Scope Reconstruction-Related
[134]				✓
[73]			✓	
[61]	✓			
[28]	✓			
[64]		✓		
[39]				✓
[65]		✓		
[135]				✓
[72]			✓	
[75]		✓		
[114]	✓			
[136]	✓			
[27]		✓		
[68]	✓			
[56]	✓			
[137]				✓
[76]		✓		
[67]				✓
[26]			✓	
[30]		✓		
[83]				✓
[84]				✓
[138]				✓
[32]				✓
[25]				✓
[25]		✓		
[139]				✓
[140]		✓		
[141]				✓
[44]				✓
[25]				✓
[66]	✓			
[82]	✓			
[142]	✓			
[59]	✓			
[143]	✓			
[71]	✓			
[70]	✓			
[106]	✓			

Table A1. *Cont.*

References	Strategic Recovery Framing	Decision Drivers and Constraints	Intervention- or Scheme-Oriented	Out-of-Scope Reconstruction-Related
[144]	✓			
[81]	✓			
[57]	✓			
[58]	✓			
[53]	✓			
[145]		✓		
[77]		✓		
[48]		✓		
[49]			✓	
[47]			✓	

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