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ACT-FLOW Framework: A Multi-Level Approach to Enabling Local Territorial Circular Processes in the Construction Sector Through Actor Networks and Material Flows

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Abstract

The transition towards circular practices in the construction sector requires integrated approaches addressing both material resource procurement and the fragmentation of local stakeholder networks. This study presents the ACT-FLOW Framework, a multi-level approach enabling territorial circular processes by integrating actor networks and material flows. The framework comprises three interconnected levels (strategies, processes, and indicators) supporting the definition, implementation, and evaluation of circular practices across building and territorial scales with an iterative refinement phase. Methodologically, it was developed through a Design Science Research approach (DSR) articulated into four steps: (1) define the scope and boundaries; (2) develop a knowledge base; (3) structure the framework and its components; and (4) validate and apply it to a real case, the Circular Design Polito Lab, a research infrastructure currently under development by the Politecnico di Torino (Italy). The results demonstrate how the framework supports stakeholder coordination, structures circular workflows, and enhances circular performance monitoring. The primary limitation is that the case study has not yet been realized; consequently, it is not feasible to conduct an ex post but only an ex ante evaluation of the results. Future research will assess the framework's capacity to foster ecosystemic conditions for circular construction practices through its longitudinal application across project phases.

Keywords: circular economy; territorial ecosystem; building sector; stakeholder network; material flow; reuse; circular indicators; multi-level framework

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1. Introduction

The transition to a circular economy is a key strategy in the European Union's policies aimed at achieving carbon neutrality by 2050 [1].

The European Parliament defines circular economy as an economic model focused on the principles of sharing, reusing, repairing, refurbishing, and recycling within a closed-loop system. The primary objective of a circular economy is to maximize the utility and value of products, components, and materials while minimizing waste generation [2].

Specifically, within the EU, the construction sector accounts for around 50% of material extraction and over 35% of total waste generation [3]. Worldwide, the production of construction materials is responsible for 55% of annual material extraction [4,5]. Furthermore, construction materials such as concrete and steel are responsible for 18% of all building-related emissions [6].

The circular economy paradigm has led to the development and testing of various strategies aimed at maintaining the highest possible quality and value of resources for as long as possible, using renewable resources with a low environmental impact [7].

Some authors [8] propose organizing existing circular building strategies into four fundamental principles: regenerating, narrowing, slowing and closing resource loops, and collaborating. However, other authors propose that strategies should be organized according to their level of circularity, arranged in a hierarchical structure based on the R framework [9,10].

Despite the attention given to the transition to a circular economy by public strategies and policies and despite the steady increase in scientific research [11], some limits to the wider adoption of circular economy principles remain. In fact, the integration of circularity strategies and principles in the construction sector remains fragmented [12]. This may be linked to the absence of clear reference indicators for measuring the degree of circularity in a construction project [13,14] and for assessing the level of implementation of circularity strategies in the construction sector [15].

Although policies promoting circular economy strategies in the construction sector—such as the reuse of materials—have been developed in some European contexts, in others, policies remain predominantly focused on waste management and end-of-life recycling, while design and prevention strategies remain less developed [16,17]. Furthermore, the recent literature emphasizes that circular design cannot be limited to the building scale, detached from its context, but requires the construction of a collaborative ecosystem of actors capable of supporting and disseminating circular practices [18]. In fact, some studies argue that the transition to the circular economy relies on a broad alliance of stakeholders, including producers, consumers, policymakers, and scholars [10]. It may therefore be appropriate to develop frameworks that support and guide decision-making processes related to circularity strategies throughout the entire lifecycle of a project [19].

Indeed, the literature contains numerous contributions related to the development of frameworks to support the implementation of circularity strategies. Some studies propose frameworks that support the definition and implementation of circular design strategies during the design [20,21] and construction phases [22–24]. Conversely, certain tools have been developed to study supply chain management processes in the construction of circular buildings based on case studies [25] or the management of a circular construction site [26]. Other contributions, on the other hand, propose conceptual tools to integrate circularity across the various phases of the lifecycle and different scales of governance [27] or to promote the adoption of smart technologies in support of circular construction [8,28].

Even in the grey literature, there are tools capable of supporting and guiding the decisions of the various stakeholders involved in a building's lifecycle toward circularity, for example, Level(s). In this case, these are tools that define an operational approach, but one that is most often focused primarily on material aspects and tends to prioritize the technical dimension [27].

In general, the various frameworks are limited in scope, addressing specific aspects such as certain eco-design strategies (e.g., DfD, reuse, etc.) or specific phases (design, construction, end of life, etc.). While the importance of collaboration among local stakeholders for the effective adoption of circular practices is recognized [29] and specific tools have been developed [30,31], the lack of engagement remains a significant barrier to the adoption of circularity practices [32]. The proposed work aims to provide a novel tool for integrating the creation of networks of local actors into the implementation of eco-design strategies within architectural projects in a given territorial context, seeking to address the research question: How can processes at the territorial level be initiated in order to enable the implementation of circular design strategies at the building scale?

To address this research question, the first step will be to contextualize the key theoretical concepts through a literature review. This will lead to the formulation of a framework designed as an operational tool to guide the planning and design of architectural projects. This will be achieved by activating processes that, starting with the creation of networks of local stakeholders, support the implementation of circular eco-design practices at the building scale. To develop the framework, a methodical approach was employed. This method involved defining the scope of application, analyzing the relevant literature on guidelines to determine the structure and constituent elements (processes and indicators), and validating the framework through a questionnaire administered to experts in the circular economy within the Italian context. The Actor and Flow Framework for Circular Building Ecosystems (ACT-FLOW framework) will be presented by applying it to the development of a demonstration project, a new research and teaching infrastructure at the Politecnico di Torino.

This paper is structured as follows. Section 2 provides a theoretical background, briefly introducing some of the concepts, such as the levels of application of circularity, circular eco-design strategies at the building scale, and the concept of a territorial circular ecosystem. Section 3 details the demonstration project, the subject of the application framework, and the context in which it is situated. Section 4 details the framework's development methodology. Section 5 presents a description of the results obtained from applying the framework to the demonstration project. Finally, Section 6 offers a critical discussion of the validation and application of the framework, the potential limitations of the adopted approach, and possible future directions for the research.

2. Theoretical Background

Research on circularity in the built environment identifies three levels of circular economy application: micro, meso, and macro [33]. From a systemic perspective, buildings can be viewed as the meso-level, urban agglomerations as the macro-level, and building components and materials as the micro-level [33]. Research on circularity has primarily focused on the recyclability and reuse potential of materials (micro-level) and the analysis of material flows (macro-level), leaving strategies and solutions at the building scale (meso-level) relatively unexplored [34,35]. According to some authors, the meso-level can also be conceived as a complex network of projects that are planned and managed under a single framework, situated at an intermediate scale between the individual building and the territorial scale [35]. The introduction of a scale that considers multiple projects aims to promote the reuse of materials and components by fostering collaborative networks [35]. The ACT-FLOW framework presented in this work, therefore, aims to effectively integrate the macro- and meso-levels, establishing collaborative networks at the local level, to promote the application of eco-design strategies at the building scale. The following subsections introduce some theoretical concepts that have guided the methodological development of the framework, in particular, which circular eco-design strategies have been considered (meso-level) and what is meant by a territorial circular ecosystem (macro-level).

2.1. Introduction to Circular Eco-Design Strategies

To understand the models, processes, and practices being used to address the transition to a circular economy in the construction sector, it is necessary to examine the design strategies that can facilitate and support its implementation at the building scale (meso-level).

A literature review has identified the most common strategies employed in both theoretical and practical contexts. These include design for disassembly (DfD) and the reuse of building materials and components. These strategies are the most frequently cited in both the scientific and grey literature [36]. In addition, strategies such as the selection of materials derived from natural resources with low environmental impact, and adaptability and flexibility of design have been shown to have a higher degree of maturity [37].

The strategies that promote the reuse of building materials and components after their initial use can be viewed from two different perspectives. Upstream strategies enable the future reuse of elements across multiple lifecycles, and downstream strategies aim to simplify the integration of reusable elements originating from disassembled buildings into new projects [38]. The first perspective, known as design for disassembly, involves a process that encourages the reversibility of construction and the reuse of components at the end of their lifecycle [21]. In this context, DfD can also be regarded as a methodological approach that leverages dry construction and prefabricated building elements to facilitate the deconstruction of structures without resorting to demolition [39]. The second, on the other hand, can be defined as design from disassembly [40] and involves the integration of reusable elements into new buildings through the additional use of digital databases that catalog these elements [41]. The strategy of reusing materials and components aims to preserve their economic value by extending their useful life [42]. The reuse of components in a new cycle can also significantly reduce resource consumption and CO_2 emissions [43]. However, this approach requires an innovative resource management method and a systemic approach to value chain integration [44]. These two strategies, briefly introduced here, are employed in this study to develop the case study project.

2.2. Introduction to Territorial Circular Ecosystems

In recent years, a number of authors have helped to define and expand the concept of the 'circular territorial ecosystem' (CTE). From a synthesis of various studies [45–48], a common vision emerges: a circular ecosystem arises from the integration of the principles of industrial ecology and those of the circular economy, taking on a territorial configuration in which various actors (businesses, public bodies, citizens, universities, and civil society organizations) collaborate to close resource cycles and generate shared value. This lineage is rooted in the industrial symbiosis and eco-industrial park tradition, where geographically proximate actors exchange resources and by-products to retain material value [49], a perspective recently extended to the construction sector, where fragmented supply chains and heterogeneous waste streams constrain feasible exchanges [50].

The most recent studies agree on the importance of governance, transparency of information flows, complementarity and interdependence among stakeholders, and the building of trust and a shared vision [45,47,51].

Based on the definitions analyzed, this study assumes that a circular territorial ecosystem is an integrated territorial system, comprising a diverse community of interconnected public and private actors who are hierarchically independent yet interdependent, and who cooperate by sharing flows of materials, economic value, and knowledge in order to regenerate resources and create shared value. These actors, coordinated by a facilitator, operate within defined (local) territorial boundaries, triggering processes of symbiosis and innovation that foster resilience and the transition towards circular economy models. This definition aims to demonstrate how a circular ecosystem is an evolving, multidimensional construct that integrates elements of innovation, governance, technology, and collaboration to promote sustainable economic models of production and consumption, closing material cycles and reducing waste.

These analyses highlight several challenges and opportunities relating to research:

- The need for cross-cutting studies to assess the impacts on the sustainability of these ecosystems [52,53];
- An understanding of the specific roles and dynamics within circular ecosystems in different contexts [46,54,55];

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- The development of integrated frameworks to manage and coordinate relationships between different stakeholders [56,57];
- The need to explore educational aspects and drivers of change at the micro-level to promote the uptake of circular practices at the local level [58].

At the same time, a few necessary measures are identified to facilitate the transition to an ecosystem of circular practices, namely

- The development of local supply chains to establish the basic infrastructure required for the development of such practices [59,60];
- The adoption of a systems-based design approach that enables all aspects of an ecosystem to be monitored from the earliest stages [61,62];
- The development of local research clusters that contribute to innovation within the system through practical experimentation with circular economy models [61,63];
- The development of a digital infrastructure (platforms and tools) to facilitate the sharing and management of data relating to these practices [62,64–67].

These actions emerge from the publications analyzed as key strategies for a transition to a circular model and are regarded as a supporting element of the ACT-FLOW Framework. This study aims to highlight how the development of CTE is a key component in facilitating the implementation of circular economy strategies, the establishment of networks between local stakeholders, and the development of systems for managing material flows.

3. Circular Design PoliTo Lab

The ACT Flow Framework will be applied to the "Circular Design Polito Lab" project at the Politecnico di Torino. This decision was made because the research group is actively involved in the design of this new laboratory, where experiments on circularity practices in the construction sector will be conducted. This was seen as an opportunity to apply theoretical concepts to a concrete case study, using the new lab as a showcase for circular practices.

The Circular Design Polito Lab project is the result of a collaboration between the Municipality of Cambiano (Italy) and the Department of Architecture and Design at the Politecnico di Torino. More broadly, the initiative is part of the ECO3R-Territorial Ecosystem for Reduction, Reuse, and Recycling—launched in 2020 by the Consorzio Chierese Servizi, a consortium for the collection and management of urban waste, and the Politecnico di Torino, with the involvement of local municipalities of the south-east area of Turin. Figure 1 represents the localization of "Circular Design Polito Lab" within the territory of the ECO3R project.

Figure 1. Geographical contextualization of the Circular Design Polito Lab. On the right, the area of the ECO3R ecosystem is represented.

The laboratory is part of the IR-CIST project, a unified research infrastructure initiated by Politecnico di Torino for the construction sector and decision-making processes concerning buildings, the city, and the territory. It involves the business community, public bodies, and citizens and is funded by the Piedmont Region through the INFRA+ call for proposals. The IR-CIST infrastructure will be organized into different types of laboratories to support research on strategic planning and decision-making, performance evaluation, prototyping, and modeling at various scales. The "Circular Design Polito Lab" is an example of this latter category. Specifically, the research and teaching activities in the lab will focus on developing sustainable and circular building practices. The aim of these activities is to foster experimentation; reduce fragmentation among actors in the construction supply chain; and promote innovative, collaborative solutions that facilitate the transition to a circular economy. The knowledge and skills developed in the lab focus on the design of reversible buildings and on providing services to local businesses for testing circular materials and technologies. The lab building is not merely a place for research and teaching activities; it is designed to serve as a tangible example of circular practices. Its design prioritizes the reuse of materials and components, with resource availability as a key guiding factor. The project is conceived as an experimental tool for generating knowledge and defining replicable models of design and reuse within the local context, enabling the development of a participatory and experimental initiative.

The ECO3R project, on the other hand, has led to the creation of a reuse hub, and an "Observatory for the Circular Territorial Economy" is currently being developed to map local material supply chains and develop specific circularity strategies for the territory [68]. In this context, collaboration with a network of local stakeholders, forming the basis of the "Circular Design Polito Lab," will enable the launch of a reuse initiative for materials, components, and systems in the construction sector. This initiative will aim to systematize skills, resources, and practices at the regional level by expanding the initial 3R-based (reduce, reuse, and recycle) approach to encompass the 10Rs principles.

The project involves the construction of a laboratory building, comprising spaces for model-making, material storage, classrooms, and offices. The load-bearing structure is planned to be realized using repurposed shipping containers, which will be modified and integrated through an iterative and adaptive process. In this process, design decisions are progressively defined based on the availability and characteristics of the materials. Many of these materials were recovered from decommissioning sites through audits conducted by the research group and the project's stakeholders.

The Circular Design Polito Lab demonstration project presents a valuable opportunity to assess the practical efficacy of the framework outlined in this article by evaluating its implementation in a real-world setting. Numerous case studies across Europe illustrate the integration of innovative practices at both the building and the urban-territorial scale. One such project is the Upcycle House, a concept by the Lendager Group developed using decommissioned shipping containers and other reused materials and components [69]. Another is the "cHOMgenius. PrototypeSystem and SharedProject" studied and developed by the Politecnico di Milano, consisting of a prototype residential building that serves as a research infrastructure for testing products, components, and systems designed to be disassembled and reversible [70,71]. Additionally, De Her, promoted by the City of Rotterdam, is a circular center focused on citizen education and the development of circular practices, built using reused materials recovered from various sources [72].

In consideration of these premises, the ACT-FLOW Framework presented in the following sections aims to translate design choices into operational practices that can facilitate the activation of local synergies and promote the dissemination and replicability of circular approaches in architectural design.

4. Methods

This study adopts a Design Science Research (DSR) approach, a paradigm in which knowledge is generated through the construction and evaluation of an artefact that addresses a real-world problem [73]. The artefact developed in this work is a framework supporting the adoption of circular practices in the construction sector. This methodological choice responds to a recurring limitation in circular economy research within the built environment, where frameworks and strategies are frequently proposed without being tested in application, leaving a gap between the knowledge generated in academic settings and its uptake in professional practice. DSR addresses this gap directly, as it requires the proposed framework not only to be designed but also to be validated and applied in a real context. Consistently with established DSR process models [74], the research is articulated into four main steps, as illustrated in Figure 2: (1) the definition of the scope and boundaries of the framework's application; (2) the construction of the theoretical background that informs the design; (3) the structuring of the framework and its components; and (4) its validation and application to a real case. This approach has a direct precedent in the same domain, as [75] employed DSR to develop and validate a framework for integrating circularity into construction sectors, thereby confirming its suitability for research seeking to make academic knowledge actionable for practitioners.

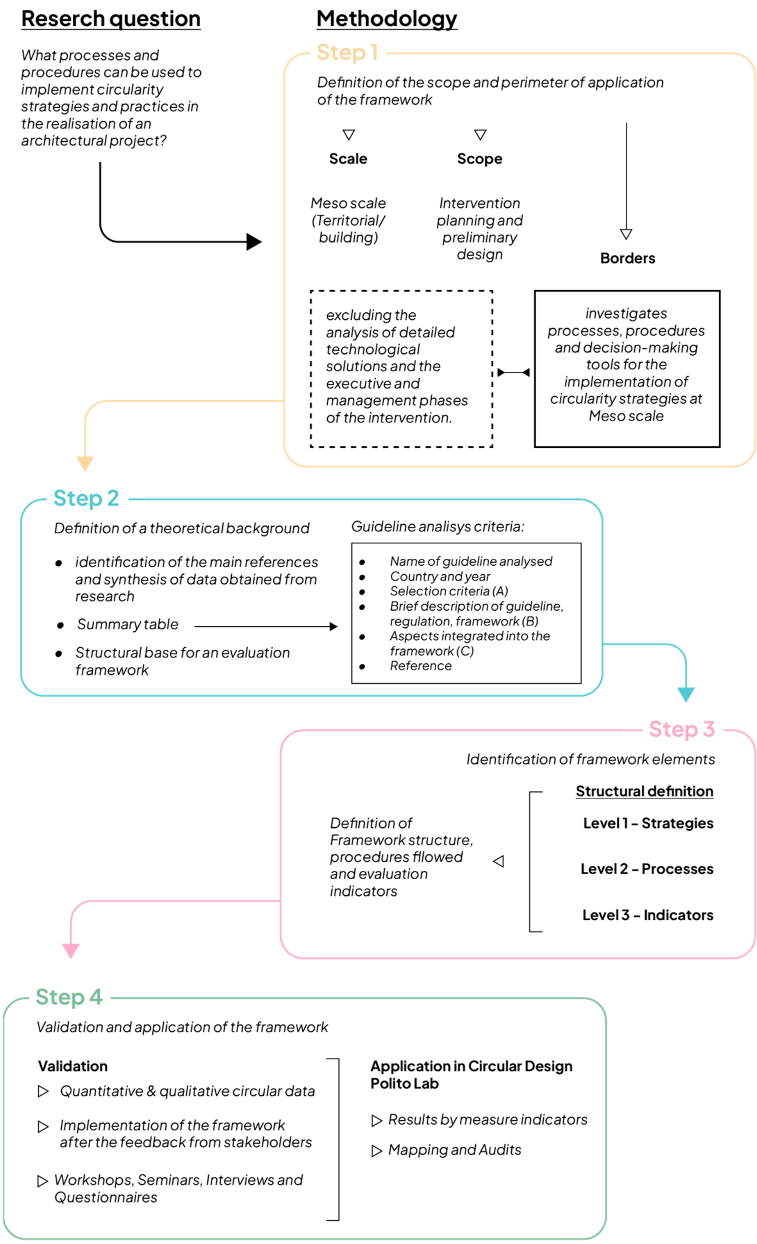

Figure 2. Flowchart describing the methodology and research process followed for the development of the framework.

4.1. Step 1—Definition of the Scope and Boundaries of the Framework

The research question we aim to answer is: How can processes at the territorial level be initiated to enable the implementation of circular design strategies at the building scale?

The framework is applied at a scale between the building and territorial levels, and its scope of application covers the project planning and concept design phases. As outlined in the RIBA framework [76], it is essential to define sustainability outcomes during the strategic definition and preparation phases. These outcomes should be aligned with applicable national and local regulations and policies. Initial feasibility assessments should also be conducted during this phase. Meanwhile, the concept design phase is when the first binding decisions regarding architectural design are made. These decisions will have a significant impact on sustainability outcomes.

The implementation of circularity strategies in architectural projects largely depends on the ability to intervene during the shaping of decision-making processes. Planning and concept design are key stages for integrating circular eco-design practices because they define the project's constraints, opportunities, and development trajectories over time [77,78]. Employing a decision-making tool in these preliminary stages, such as an operational framework to guide the design process, facilitates the identification and implementation of processes and procedures. These measures enable the effective implementation of circularity strategies within the built environment at various scales.

4.2. Step 2—Analysis of Guidelines to Identify Processes and Indicators

A review of the guidelines, regulations, and other tools currently used by stakeholders in the AEC sector enriches the theoretical analysis outlined in Section 2, by identifying processes that support the implementation of circularity strategies at various levels and the qualitative and quantitative indicators for assessing the circularity of an architectural project. Documents that are used to support decisions and assessments on circularity in the construction sector have been selected and analyzed. Table A1 in the Appendix A presents the results of the analysis, summarizing the following information:

- Reasons for choosing the guideline;
- A brief description of the guideline and what it covers;
- The aspects identified and subsequently incorporated into the development of the framework proposed in this paper.

Numerous studies in the literature identify tools and methods for assessing circularity [14,27,79–81]. While numerous guidelines were identified, this section and Table A1 in the Appendix A list only those relevant to the development of the work presented in this paper. The primary criterion for selecting the guidelines analyzed was their operational relevance. Based on this criterion, guidelines were selected for use as applied tools for planning, evaluating, or certifying construction projects [27]. Another selection criterion concerned the context in which they were developed. Specifically, documents developed within the European context or applicable to that context were selected. The types of documents analyzed, therefore, include both public regulations and assessment protocols developed by private entities, which define relatively codified and applied processes and procedures.

The analysis of the guidelines indicates that the effective implementation of reuse processes depends largely on clear definitions of operating procedures and the roles of stakeholders throughout the supply chain. For instance, the DIN 91848 standard identifies the actors commonly involved in recovery processes and codifies processes for the acquisition, selection, and management of materials and components intended for reuse, using specific tools such as pre-demolition audits [82]. Another example of a norm that promotes circular practices in end-of-life management is the French AGEC Law (2020) [83]. This law enables on-site sorting by qualified operators and ensures that selected materials can be reused without being classified as waste. Furthermore, the FCRBE project guidelines underscore the significance of communication and outreach to stakeholders in the construction sector as a prerequisite for integrating the developed tools into operational practices [84]. While these documents acknowledge the need to build networks of stakeholders, they do not provide operational processes or procedures for engaging supply chain stakeholders. This is because they were developed in local contexts where networks and systems of stakeholders, along with infrastructure supporting reuse processes, are already established. In a regional context such as Italy's, where circular design practices are not yet sufficiently widespread, it is necessary to identify processes for engaging actors in the construction supply chain. To address this gap, it was necessary to draw on the scientific literature on stakeholder network mapping and stakeholder engagement activities [13,85]. The analysis indicates that identifying the relevant stakeholders with respect to systemic circularity objectives is a crucial phase that requires selecting stakeholders based on their alignment with the pursued circularity values and their roles within the value chain. Stakeholder engagement should be approached as a collaborative, ongoing process that transparently involves all actors in the supply chain to co-design reuse and circular solutions [86]. Engagement activities involve using various channels (events, seminars, and workshops) to build ongoing relationships through dialogue and knowledge exchange [86] and to periodically evaluate results achieved to adapt strategies and the composition of the network [85].

In addition to processes and stakeholders, the guidelines provide indicators to evaluate performance in pursuit of circularity principles. Assessment methods and numerical indices are essential for quantifying specific aspects of circularity and, consequently, for optimizing responses to project requirements [81]. Guidelines, such as Level(s) and or those developed by the World Business Council for Sustainable Development and DGNB, indicate that material flow management is a key factor in implementing circularity practices. The indices provided by these documents assess the flow of circular materials and distinguish between input flows—necessary for the realization of a product or building project—and output flows, which indicate the quantity of materials to be managed at the end of their life [87–89]. The circularity of material flows related to a project is calculated by assigning a score to the origin of input materials, i.e., those derived from reuse or recycling processes and evaluating the treatment of output materials according to the waste hierarchy [90]. Regarding metrics and indicators related to stakeholder engagement, the guidelines reviewed do not provide specific indicators for reference. Therefore, it was necessary to rely on the scientific literature.

4.3. Step 3—Development of the Framework Structure Based on the Data Collected from the Analysis

This section presents the levels that define the framework, as well as the operational procedures and indicators, both developed based on an analysis of the guidelines and regulatory framework outlined in Section 4.2. These documents provided the foundation for developing a set of processes that support the application of circular eco-design strategies. The development of procedures and indicators results from a critical review of the analyzed information, aimed at translating its principles into operational processes and monitoring metrics for use in the early stages of the design process.

The framework is structured across three levels: strategies, processes, and indicators. The following subsections outline the components of the framework.

4.3.1. Level 1: Strategies

The first stage of the framework involves identifying which circular eco-design strategies will be pursued during the project's development, as well as how to link them to the processes required to implement them effectively. Circular eco-design strategies vary in nature, and their adoption must be assessed on a case-by-case basis [91]. For the selection and implementation of strategies during the planning phase, the framework proposed by [36], based on the Plan–Do–Check–Act concept recommended by ISO/TR 14062 [92], was used as a reference and appropriately adapted by creating a tabular checklist. The tabular checklist is used to define project objectives in terms of sustainability and circularity, select the most appropriate circular eco-design strategies to incorporate into the project, and establish a process for implementing them.

4.3.2. Level 2: Processes

The second level identifies the processes to be implemented to ensure the smooth and consistent application of the circular eco-design strategies identified in the previous level. The critical evaluation of the guidelines indicates two essential processes for executing a project that aims to incorporate circularity principles: the creation of stakeholder networks and the management of material flows.

Stakeholder networks are essential to the project, as they provide knowledge, services, and infrastructure to support the implementation of circular strategies. To initiate the process of establishing stakeholder networks, two complementary subprocesses can be followed:

1. Stakeholder network mapping, aimed at identifying their geographical location, indicating the number of stakeholders involved in the circular economy project network, and analyzing their geographical distribution in relation to the project site [93].
2. The implementation of stakeholder engagement activities, developed through discussions, interviews, seminars, and workshops, which enable the identification of needs and expectations and the involvement of local stakeholders in the project process [8,85,94,95].

Effective management of material flows throughout a project's lifecycle is essential for promoting the reuse of materials and components in the construction sector [96]. As outlined in the guidelines [87,89], material flows can be divided into two categories: incoming flows and outgoing flows. To achieve a circular procurement process, it is necessary to identify incoming materials with suitable characteristics (e.g., reused, recycled, or bio-based) and to adopt technological systems that enable materials to be reused or recycled at the end of their life.

4.3.3. Level 3: Indicators

At the third level, qualitative, semi-quantitative and quantitative indicators are identified for the purpose of evaluating and monitoring the procedures adopted for stakeholder mapping and engagement and for the management of material flows.

When mapping networks of actors and monitoring stakeholder engagement activities, several authors suggest incorporating social indicators [13,85]. In this framework, these two subprocesses are supported by a number of qualitative (QL), semi-quantitative (SQT), and quantitative (QT) indicators. The indicators are listed below and reported in detail in Table A2 in the Appendix A.

The indicators for stakeholder network mapping are

- QL1—Territorial consistency of the network.
- QT2—Number of active members in the network for each category involved.
- SQT3—Geographical distribution of stakeholders in relation to the project site.

The indicators for stakeholder engagement activities are

- QL4—Existence of structured moments to co-define values and CE vision.
- QT5—Number of activities, participants, and organizations involved.

- SQT6—Diversity of active stakeholders.

In addition, quantitative indicators, selected and adapted from the guidelines analyzed, were identified for the management of material flows. The indicators are briefly listed below and detailed in Table A2 of the Appendix A:

- QT7—Material stock (MS) and material intensity (MI). The MS is the total quantity of materials used in the construction of a building.
- QT8—Circular inflow–material origin. It is an indicator that evaluates the materials used in the project based on their origin (renewable materials, materials produced using MPS, reused materials, etc.).
- QT9—Circular outflow–circularity score. It is an indicator that assesses the end-of-life scenarios for the materials used in the project.

Results are reported through a single reporting structure applied to all indicators, qualitative and quantitative alike (assessment criterion, evidence, and comment). The "assessment criterion" states the rule against which the indicator is read; the "evidence" presents the result obtained; and the "comment" provides a critical evaluation of the result, including, where relevant, its consistency with other indicators. The indicators are assessed directly by the research team based on the documented evidence from research and network activities (activity records and reports, workshop documentation, and project materials).

4.4. Step 4—Validation and Implementation of the Framework

Before implementing the ACT-FLOW framework in the Polito Lab Circular Design project, its elements (strategies, processes, and indicators) were validated. The ACT-FLOW Framework was validated through an expert questionnaire conducted with a non-probabilistic purposive (criterion-based) sampling strategy, consistent with the study's exploratory and content-validation aims. This type of study requires the deliberate engagement of subjects with specialized knowledge rather than a statistically representative sample [97,98]. Experts were selected against two inclusion criteria:

I. Demonstrable thematic expertise in at least one domain relevant to the framework (circular economy, circular construction, material reuse, and design for disassembly or sustainable architecture);
II. Familiarity with the territorial context in which the framework and its demonstration case are situated, so as to assess the framework's applicability to local territorial ecosystems.

On this basis, a panel of 15 experts was invited to participate. Fourteen of these completed the questionnaire, providing a complete set of responses with no partial returns. The panel size is consistent with other studies for expert-based content validation, which considers a panel of approximately 10–15 qualified [75] experts adequate for this purpose. The panel combined academic and professional profiles: 7 respondents were architects/engineers, 6 academic researchers, 2 professors, and 2 industry professionals (multiple roles could be indicated). Professional seniority was high because 7 experts reported more than 20 years of experience, 4 between 5 and 10 years, and 3 fewer than 5 years, so that 11 of the 14 respondents (79%) had at least more than 5 years of experience. The most frequently declared areas of expertise were sustainable architecture (8), material reuse/design for disassembly (7), circular economy (6), and circular construction (6). The composition of the panel is summarized in Table 1.

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Table 1. Profile of the expert panel for the questionnaire (*n* = 14). * Respondents could select more than one role/area of expertise, so totals therefore exceed 14.

Characteristic	Category	N°
Professional role *	Architect/Engineer	7
	Academic researcher	6
	Professor	2
	Industry professional	2
	Other	1
Years of experience	>20 years	7
	5–10 years	4
	<5 years	3
Area of expertise *	Sustainable architecture	8
	Material reuse/design for disassembly	7
	Circular economy	6
	Circular construction	6
	Urban/regional planning	1
	Other	3

The theoretical consistency of the framework's elements was assessed using the SMART approach [99,100], a validation methodology based on five criteria. In detail, these criteria are

- Specific, which refers to the clarity and unambiguous definition of the criterion;
- Measurable, which refers to the possibility of assessing it using qualitative or quantitative indicators;
- Achievable, which indicates whether it is feasible to implement it in practice in a real-world context;
- Relevant, which refers to the contribution that the element makes towards achieving the objectives of circular ecosystems in the construction sector;
- Time-bound, which relates to the ability to monitor its performance over time.

Each criterion was evaluated using a qualitative scoring system to determine whether it was fully met, partially met, or not met. The elements that met the SMART approach criteria were considered validated and included in the final version of the framework, while those that did not meet one or more criteria were further modified and re-evaluated or excluded. The results of the questionnaire will be presented and discussed in Section 6.4.

By applying the ACT-FLOW Framework to the Circular Design Polito Lab project currently under development, it was possible to verify the operational functionality of the elements introduced, thereby providing insights to simplify and define them with greater precision. Figure 3 provides a summary diagram of the framework elements discussed in this section.

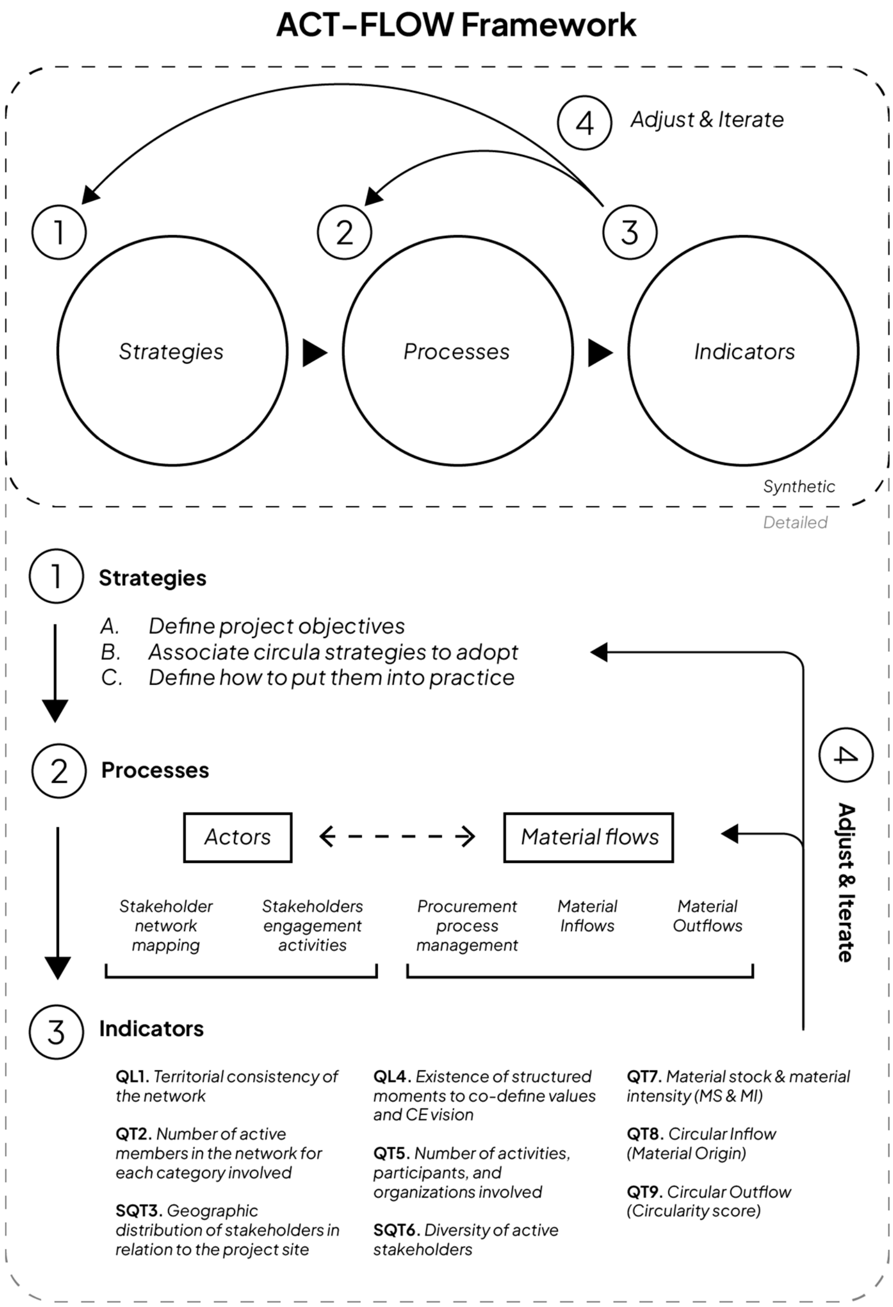

Figure 3. Summary of the components of the ACT-FLOW framework and the workflow followed.

5. Results of Framework Application

This section presents the results obtained by applying the ACT-FLOW Framework to the Circular Design Polito Lab demonstration project, as introduced in Section 4.4. Figure 4 illustrates and summarizes the results of applying the framework to the demonstration project, which are discussed in the following sections.

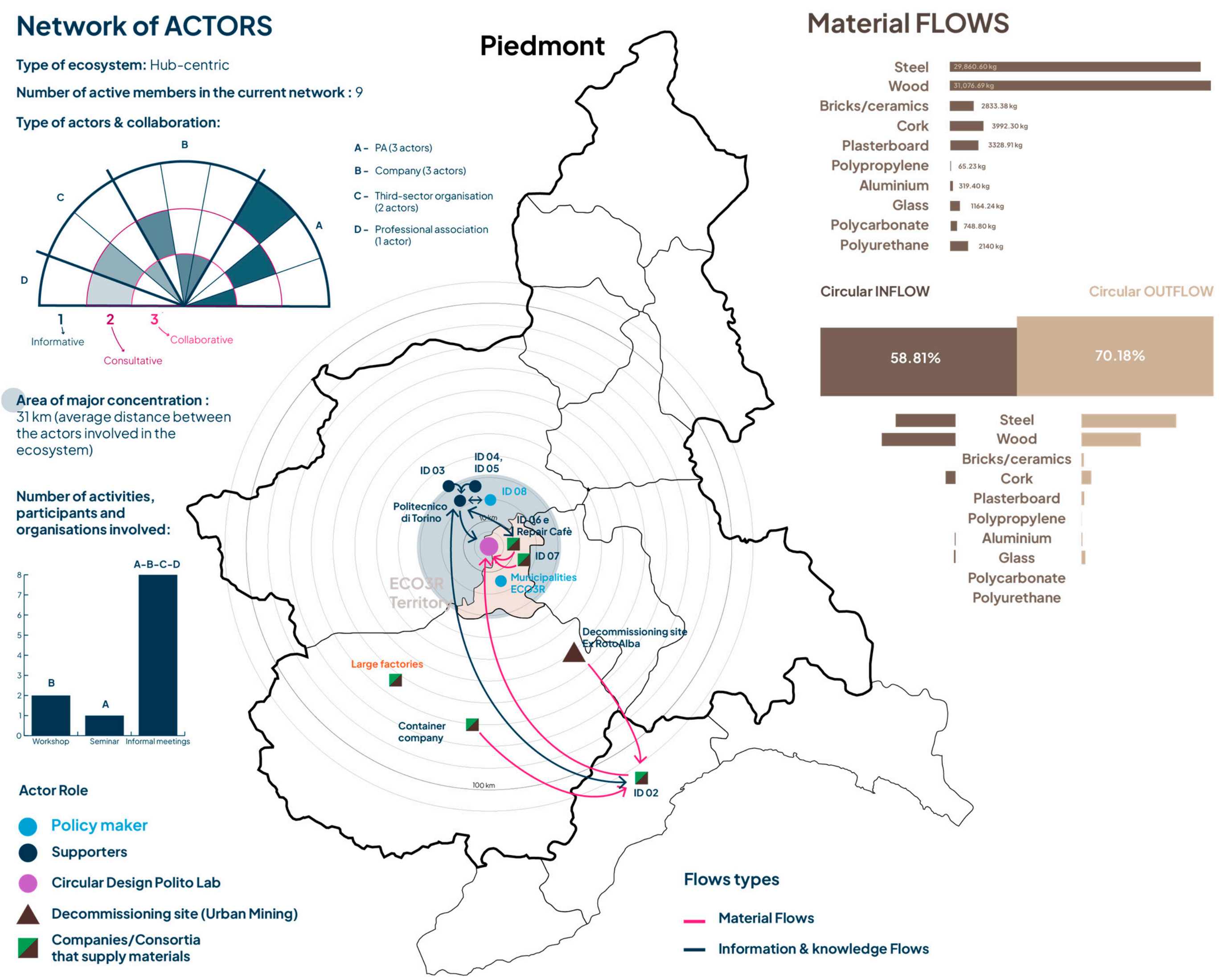

Figure 4. Summary of the results obtained by applying the ACT-FLOW framework to the Polito Lab Circular Design project.

5.1. Level 1: Strategies

At the first level, as shown by Table A3, the project's sustainability and circularity objectives were identified, along with the corresponding circular eco-design strategies, and several key strengths upon which to base the development of implementation processes. In the development of the Circular Design Polito Lab, the main goals are to realize innovative research and teaching infrastructure as a manifesto of circular practices and to enhance the circular territorial ecosystem among local stakeholders. These goals are related to the circular strategies of reuse of material, design for disassembly, and creation of network-based or collaborative relationships.

5.2. Level 2: Processes

5.2.1. Stakeholder Network Mapping and Engagement

The subsequent sections detail the process that was followed to develop the network of stakeholders and engage them in support of the project. The analysis's structure enabled the identification of stakeholders present at the local level and those interested in contributing to the developing ecosystem. The results are presented below, divided into the two main processes used: stakeholder network mapping and stakeholder engagement activities.

The stakeholder network mapping resulted in the establishment of a comprehensive database of stakeholders within a 150 km radius, encompassing both public and private entities from diverse sectors with a connection to the construction industry. In Table 2, the data related to stakeholders mapped are reported.

Table 2. Stakeholder database.

ID	Business Sector	Localization (Distance from the Site of Project)	Contribution to the Project's Circularity
01	Education, training, and research	Torino (TO) (20 km)	Project development and planning
02	Decommissioning and waste management	Cairo Montenotte (SV) (125 km)	Supply of materials and components recovered from decommissioning sites
03	Social and cultural activities	Torino (TO) (23 km)	Support in the experimentation of practices related to circularity
04	Assistance to member companies	Torino (TO) (20 km)	Dissemination of know-how related to circularity
05	Assistance to member professional	Torino (TO) (21 km)	Dissemination of know-how related to circularity
06	Waste management and treatment	Chieri (TO) (6 km)	Supply of reused materials and components
07	Supplier of building materials	Chieri (TO) (11 km)	Supply of reusable components
08	Territorial government	Torino (TO) (20 km)	Regulatory support and public incentive provider
09	Territorial government	Cambiano (TO) (0.5 km)	Project planning support

This activity of cataloging enabled the identification of the initial actors in the ecosystem, as well as the formulation of hypotheses regarding their roles and the flows of knowledge and materials that could potentially be mobilized, while taking their geographical distance into account. To facilitate understanding, it was essential to create a map showing their locations within the territory (Figure 5). The mapping revealed that most stakeholders are located within a 20–25 km radius of the project area in Cambiano, in the province of Turin, while only one stakeholder is located in a neighboring region (Liguria, 125 km away). The decommissioning company (ID 02) played a pivotal role in supplying materials from its own decommissioning site, which is located approximately 64 km from the project area. This work highlighted the local nature of the ecosystem initially created.

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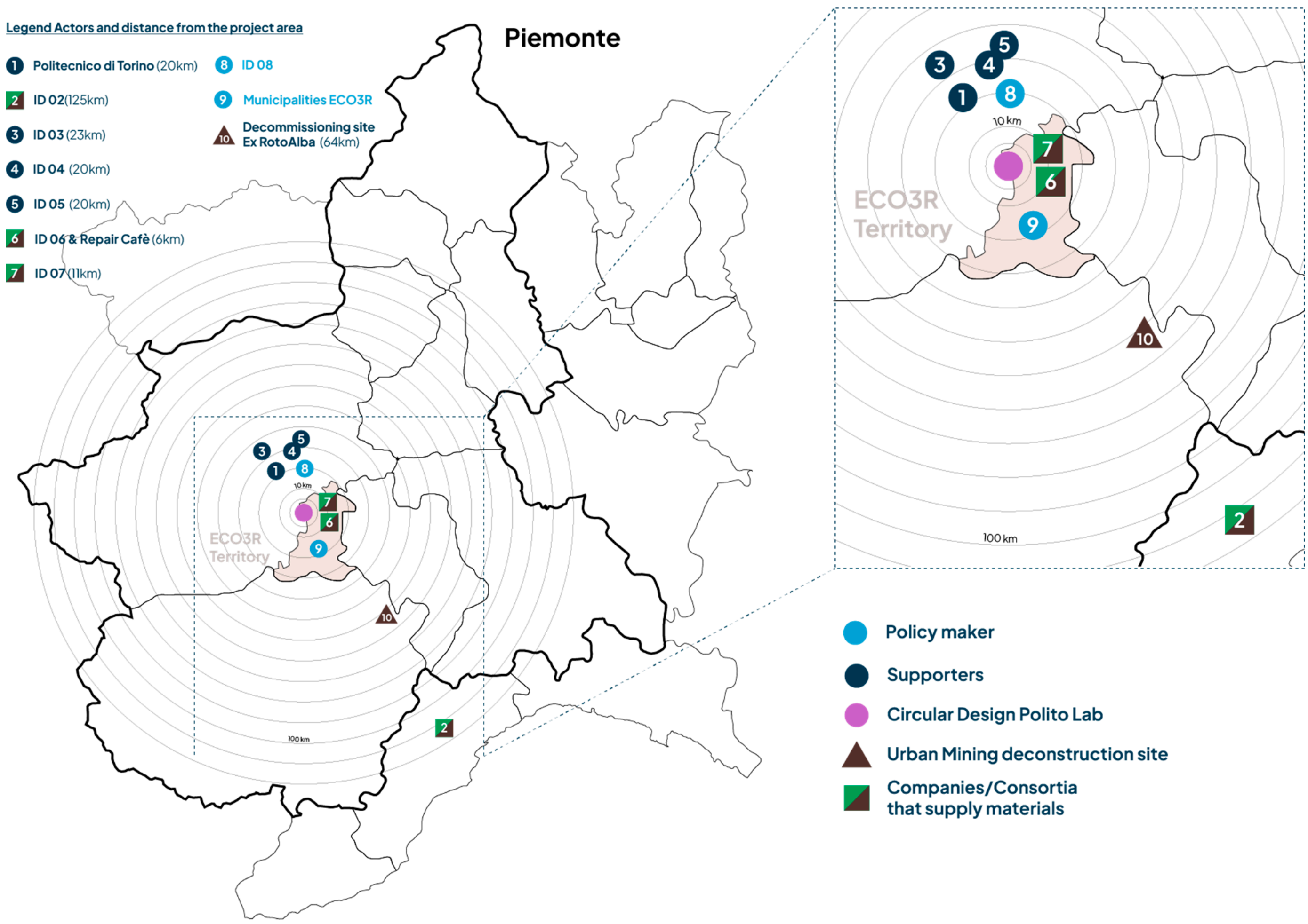

Figure 5. Geographic locations of the stakeholders involved in the project.

In organizing the various stakeholder engagement activities, the first step was to hold introductory meetings with the relevant stakeholders. These meetings opened a dialogue on circularity at the local level and introduced the project, which was still in its planning phase, to the local entities involved. The application of the methodological framework demonstrated that certain activities, such as workshops, are particularly effective in fostering the active, structured involvement of the previously identified stakeholders. Two complementary workshops, conducted with a project partner in April 2024 and January 2026, were held in total, along with several seminars and introductory meetings with identified stakeholders. The initial workshop (Figure 6) enabled stakeholders to assess their current situation by analyzing their positioning within the relevant European context and clarifying their medium-to long-term strategic objectives. This phase facilitated the establishment of a shared knowledge base, which proved useful for identifying constraints, opportunities, and areas for potential development in line with the principles of the circular economy. The second workshop focused on defining the actor's role within the circular ecosystem currently under development, exploring possible actions to be taken, and organizing them into a timeline. This tool enabled the conversion of the identified strategies into a sequence of operational actions, facilitating an understanding of priorities and interdependence among actions, as well as planning their implementation timelines.

Figure 6. Photos from the workshop held at a partner company of the "Circular Design Polito Lab" project.

The participatory process, initiated through workshops, fostered a shared reflection on the actor's position within the circular ecosystem, enabling the mapping of relationships and material and immaterial flows from a geographical perspective. This approach clarified existing and potential connections among stakeholders, thereby enhancing systemic understanding of the context and facilitating the identification of operational synergies. The primary constraints pertain to the implementation of the workshop format with a sole partner actor, due to the time required, which is not always compatible with the company's availability. However, this experiment proved useful for testing the model, with a view to extending it to other actors in the ecosystem.

5.2.2. Management of Material Flows

This section details the steps for establishing a circular procurement process based on the knowledge and resources provided by stakeholders. A key aspect of defining a circular procurement process is managing material flows (inputs) to support project implementation, as this is a crucial factor in making circular design choices. The objective of this process is to transform locally available end-of-life materials and components into resources for new projects. In the initial phase, detailed inventories and catalogs of the materials available in the area were compiled. The objective was to incorporate as many reused building materials, products, and components—or those characterized by a high degree of circularity—into the project as possible. The analysis identified three sourcing sites: a demolition site, a municipal collection center, and a storage site for decommissioned shipping containers. Material procurement was therefore organized at the local level, specifically within a maximum distance of 125 km, necessary to reduce logistics-related costs and emissions. The supply network created extends across Piedmont and Liguria and utilizes the available materials in the regional territory (Figure 7). These materials may have different origins and come from demolition sites or from waste and by-products of local companies.

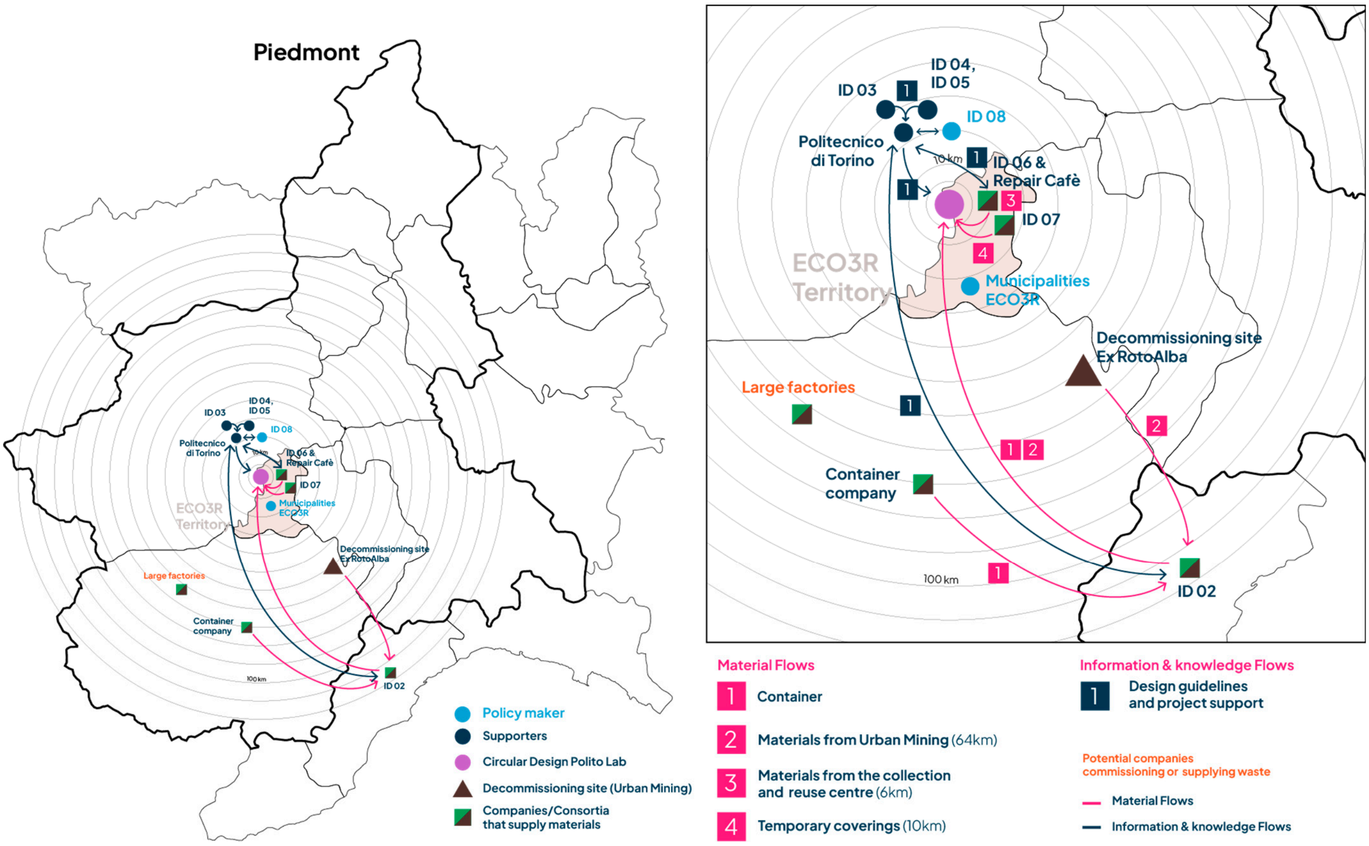

Figure 7. Map of the main flows of materials and knowledge.

Thanks to the collaboration with a decommissioning company (ID 02), materials and components from a building under demolition were recovered (Urban Mining). The creation of a quantitative database of materials and components first established an initial number of reusable materials. The inventory supported and facilitated the coordination of component recovery and dismantling operations, enabling identification of their locations on the demolition site, assessment of their recoverability (considering possible presence of hazardous substances), and definition of any necessary preparation steps for reuse. In addition, the decommissioning company's support facilitated the recovery of decommissioned shipping containers from a local logistics company. These containers form the load-bearing structure of the Circular Design Polito Lab laboratory building.

A bill of materials was created by combining the list of reclaimed materials with other materials and components needed to complete the initial core of the Circular Design Polito Lab project. The list of reclaimed materials and the bill of quantities provided an initial set of data, both qualitative and quantitative, useful for assessing the circularity of the project from a material perspective, as exemplified by the application of the selected quantitative indicators (QT7, QT8, and QT9).

5.3. Level 3: Indicators

The following sections explain the results for actor-level indicators related to stakeholder network and engagement, which range from QL1 to SQT6, and the material-flow indicators, which range from QT7 to QT9.

5.3.1. QL1—Territorial Consistency of the Network

This indicator classifies the network's configuration along two axes: its topology, whether relationships are centred on a lead actor (hub-centric) or horizontally distributed

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and self-regulated, and its geographical scale of operation. Since it is a qualitative indicator, QL1 yields a categorical reading rather than an ordinal result.

At present, the network of relationships is heavily centred around a lead actor, the Politecnico di Torino, which engages, selects, and coordinates the other stakeholders, both in relation to the local area and to the definition of circular economy objectives. This does not exclude the possibility that, over time, the initial orientation may change, evolving into a more horizontal and self-regulated system. The geographical context of reference can be traced to a regional scale, even though most flows and interactions take place at the local (provincial) level.

This indicator classified the network as hub-centric at the regional scale, with prevailing local operations. This configuration is consistent with an initiating, university-led network and with the limited membership (QT2) and the ad hoc, largely bilateral activities (QT5): coordination currently radiates from the hub rather than circulating among peers. The classification is not a permanent state because the network may evolve toward a more horizontal, self-regulated configuration as participation deepens, but capturing the present topology establishes the baseline against which that evolution can be tracked.

5.3.2. QT2—Number of Active Members in the Network for Each Category Involved

The indicator is read not as an absolute count but against the expected size for an initiating hub-centric ecosystem and against the balance across stakeholder categories.

The current network has only nine active members, drawn predominantly from the public sector and private firms, with public actors setting standards and promoting circular practices, while the private sector experiments with and implements innovative solutions.

Consistent with the hub-centric configuration identified in QL1, a membership of this size is more consistent with an early-stage, university-led network than with a mature ecosystem. The public–private composition provides the regulatory experimental complementarity needed in the initiation phase, but the limited overall number constrains the redundancy and resilience of the network.

5.3.3. SQT3—Geographical Distribution of Stakeholders in Relation to the Project Site

Stakeholder proximity is measured as the arithmetic mean of the distances from each stakeholder to the project site and assessed against predefined distance bands (0–20 km = local; 21–60 km = regional; >60 km = multi-regional), which classify the spatial reach of the network. The mean distance of stakeholders from the project area, calculated as the arithmetic mean of the measured distances (31 km), falls within the regional range of 21–60 km. The ecosystem is assessed as territorially proximate, confirming the local-to-regional character of the network. This proximity is coherent with the design from availability approach. Read together with QL1, it reinforces the picture of a spatially concentrated, locally operating ecosystem, consistent with the regional-scale but local-operation finding.

5.3.4. QL4—Existence of Structured Moments to Co-Define Values and CE Vision

This indicator was considered satisfied when participatory formats are in place, involve multiple stakeholders, and serve an explicit value and vision-setting function rather than information transfer alone. Participatory governance formats are present and recurring, taking the form of workshops, seminars, informational meetings, and coordination discussions. Their existence and the orientation toward active involvement are positive signals. However, as detailed in Section 5.3.5, participation to date has been predominantly bilateral and occasional, and the formats have functioned mainly as information and coordination channels rather than as settings for the joint definition of shared values and a common CE vision. The indicator is therefore assessed as only partially satisfied: the structures exist, but their co-definition function is not yet realized.

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5.3.5. QT5—Number of Activities, Participants, and Organizations Involved

To date, the activities carried out have been few (two workshops, a few seminars, and eight introductory meetings) and ad hoc (involving individual stakeholders), rather than involving multiple stakeholders participating in the same activity. This quantitative profile constrains the "circular value" targeted in the initial phase and confirms the difficulty in identifying coordinated opportunities for dialogue among the stakeholders involved in developing the same ecosystem. Read together with Section 5.3.4, it explains why participatory governance is assessed as partially satisfied rather than satisfied: the formats are in place, but the intensity and multilateral character of participation required for genuine co-definition are not yet present.

5.3.6. SQT6—Diversity of Active Stakeholders

Diversity is assessed along two dimensions: the range of stakeholder types active and the depth of their engagement (informative/consultative/collaborative, as defined above and detailed in Table 3). The categories primarily involved in this initial phase include four stakeholder types, engaged at three levels: public agencies, companies, third-sector organizations, and category associations. As Table 3 shows, of the nine active members, four are engaged collaboratively, four consultatively, and one only at the informative level. The engagement informative refers to sporadic or occasional interactions among stakeholders with the objective to inform and keep local authorities up to date, without a mandatory formal or ongoing commitment. The engagement consultative means sporadic interactions with a formal commitment with the objective to involve stakeholders in decision-making processes as an integral part of the network. The collaborative engagement means a deeper and more sustained involvement that goes beyond simple cooperation, involving a strategic partnership based on common objectives.

Table 3. Table identifying the level of involvement of the stakeholders in the ecosystem.

ID	Type	Level of Engagement
01	A: University (Politecnico di Torino)	3 = collaborative
02	B: Company	3 = collaborative
03	C: Non-profit entity	3 = collaborative
04	D: Category association	2 = consultive
05	D: Category association	2 = consultive
06	B: Company	3 = collaborative
07	B: Company	2 = consultive
08	B: Public agency	1 = informative
09	B: Public agency (Municipality ECO3R)	2 = consultive

The range of stakeholder types is satisfactory for an initiating ecosystem and supports the network's multi-actor ambition. The depth, however, is uneven because fewer than half of the members are engaged at the collaborative level and the public agencies (pivotal for the regulatory leverage) remain at the informative or consultative level. Diversity is therefore assessed as partially satisfied because the composition is adequate, but converting consultative and informative relationships into collaborative ones is the priority.

5.3.7. QT7—Material Stock (MS) and Material Intensity (MI)

Material stock and material intensity values, distinguished by material type, are used to calculate the circular inflow and circular outflow indicators. As shown in Table 4, the reported values correspond to the quantities of materials that constitute the various components and systems planned to be incorporated in the Circular Design Polito Lab project.

These values are extracted from the preliminary bill of quantities realized for the planning phase. The total value of material intensity for the project is 238.17 kg/m^2.

Table 4. Material stock and material intensity.

ID	Material Typology	Material Stock [kg]
01	Steel	29,860.60
02	Wood	31,076.69
03	Bricks	2833.38
04	Cork	3992.30
05	Gypsum	3328.91
06	Polypropylene	65.23
07	Alloy	319.40
08	Glass	1164.24
09	Polycarbonate	748.80
10	Polyurethane	2140.00
	Total	75,529.55

In Table S1 of the Supplementary Materials, a detailed bill of quantities, from which the value reported in Table 4 has been extracted, is provided.

The materials used with the greatest total mass are wood and steel. These materials form the building's load-bearing structures, which include the shipping containers and ancillary timber structures. Additionally, wood is a prevalent construction material in interior finishes, such as for substructures in drywall partitions and stud frames. This underscores its wide-ranging application in various layers of building structures. Cork and polyurethane are used exclusively as insulation materials, while polypropylene is used as a waterproofing membrane. Brick and ceramic tiles are used for flooring. The material intensity, calculated as the ratio of the stock material to the building's total surface area of 317 m^2, is 238.17 kg/m^2.

5.3.8. QT8—Circular Inflow–Material Origin

The typology-specific circular inflow value is calculated by multiplying the relative value of material stock by a coefficient that "weights" the material's origin (e.g., reused, biobased, recycled, etc.). Table 5 shows the typology-specific value and the total value, which is the sum of the typology-specific value. For completeness, the value of "ingoing circularity"—defined as the ratio of circular inflow to material stock—is also reported for each material typology and total flow.

Table 5. Circular inflow.

ID	Material Typology	Circular Inflow [kg]	Ingoing Circularity [%]
01	Steel	18,252.30	61.1
02	Wood	22,495.19	72.4
03	Bricks	0.00	0.00
04	Cork	2994.23	75.0
05	Gypsum	0.00	0.00
06	Polypropylene	0.00	0.00
07	Alloy	222.55	69.7
08	Glass	453.60	39.0
09	Polycarbonate	0.00	0.00
10	Polyurethane	0.00	0.00
	Total	44,417.87	58.8

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The results indicate that the highest CI and ingoing circularity values are associated with materials such as wood and cork, as they are made from certified renewable resources. Steel is a highly regarded material due to its association with recycled components, such as shipping containers. Furthermore, steel elements—such as the beams and columns of the foundation structure—also exhibit a certain degree of circularity, as they are made from recycled material. Aluminum and glass have also been found to be highly effective, given that a portion of the windows and doors utilized in the project have been reused. The project's overall ingoing circularity value is 58.81%.

5.3.9. QT9—Circular Outflow–Circularity Score

Similarly, the typology-specific circular outflow value is calculated by multiplying the relative value of material stock by a coefficient that considers different end-of-life scenarios for the material (e.g., prepared for recycling, prepared for disposal, sent to a landfill, etc.). Table 6 shows the typology-specific value and the total value, which is the sum of the typology-specific value. For completeness, the value of "outgoing circularity"—defined as the ratio of circular outflow to material stock—is also reported for each material typology and total flow.

Table 6. Circular outflow.

ID	Material Typology	Circular Outflow [kg]	Outgoing Circularity [%]
01	Steel	28,902.20	96.8
02	Wood	18,103.34	58.3
03	Bricks	708.35	25.0
04	Cork	2994.23	75.0
05	Gypsum	832.23	25.0
06	Polypropylene	32.62	50.0
07	Alloy	266.75	83.5
08	Glass	1164.24	100
09	Polycarbonate	0.00	0.00
10	Polyurethane	0.00	0.00
	Total	53,003.95	70.2

Steel is the most significant contributor to circular outflow, as it is associated with the use of components designed for use in fully reversible technological solutions. A high CO value—and, therefore, a high outgoing circularity value—is also associated with glass and aluminum, as these materials are used in doors and windows and are expected to be recovered and reused at the end of the building's life. The CO value for other materials stems primarily from recycling made possible by the adoption of disassembly principles during the design phase. These principles include separating materials and components across the building's layers, enabling effective deconstruction at the end of the building's life. The project's outgoing circularity value stands at 70.20%.

6. Discussion

Several existing frameworks adopt a multi-scalar perspective and emphasize that circularity depends on strong relationships across actors along the value and supply chains [101]. In this sense, the concept of a territorial circular ecosystem connects local circular practices with cooperation within actors, geographical proximity, and institutional support [101,102]. The originality of the ACT-FLOW Framework lies in the integration of two dimensions that are often treated separately in the literature: the relational–spatial dimension of local stakeholder networks and the material–spatial dimension of material flows and stocks. By embedding stakeholder network mapping and material flow analysis into the architectural design process, the framework shifts circularity from an ex post assessment of environmental impacts to a contextualized and operational design methodology.

6.1. Findings of the Research

The first finding of the application of the framework concerns the role of actor mapping and stakeholder engagement. These aspects are key to building actor networks and unlocking the spatial dimension of the circular economy in the construction sector. This type of study is essential for understanding the concept of "territorialism" of the circular economy through a local actor network analysis and its importance, aligning with previous studies on local network dynamics [19,103,104]. Otherwise, a key aspect of the framework is its incorporation of an innovative assessment of the network of actors and their engagement as critical components for advancing circular practices. In fact, the indicators developed can be useful for monitoring the evolution of the network, the capacity of material stocks, and the actors' needs. The methodology used enables the theoretical aspect of circularity to be transformed into operative procedures for the development of an architectural project, defining when, how, and which network of actors can develop a circular process through operational governance methods. The main contribution of the ACT-FLOW framework lies in its capacity to move beyond describing circularity and instead make it actionable at the local scale. It achieves this by establishing a sequence of actions that engage stakeholders and connect them to material flows and design decisions. This approach stands out from many existing frameworks because it combines actor mapping, stakeholder engagement, and the spatial interpretation of material flows. This combination of elements informs reuse-oriented design practices. However, many frameworks remain conceptual or focus primarily on governance, so this approach is innovative and valuable. While previous studies highlight the importance of stakeholders, governance, and data [101,102,105,106], ACT-FLOW clarifies how these elements can be coordinated within a multi-level process to support the development of local circular strategies. By connecting territorial governance (macro-level) with buildings and materials (meso-level), it reveals the interdependencies between decisions, actors, and resource flows.

The second finding concerns the interdependence between scales of circularity application. In fact, the framework enables more effective correlation between the practical aspects of circularity at the macro- and meso-levels. By applying this framework to a case study, it was possible to demonstrate that the determination of material flows depends on identifying the actors involved in the network. As demonstrated in [77], the pursuit of circularity practices entails more than the selection of materials; it requires establishing collaborative networks and implementing them at various stages of the project. The involvement of new actors in a project can contribute to the development of new materials and the application of new technical expertise. This can lead to changes in the quantitative values of material-related indicators and affect the network of actors involved. Therefore, the identification of processes for creating networks of actors and the definition of material flow management processes, along with related qualitative indicators, enable the establishment of replicable procedures. These tools empower project managers and developers by enabling them to monitor the implementation of circularity strategies at various levels.

6.2. Practical Implications of the ACT-FLOW Framework

The ACT-FLOW Framework has been developed to meet the needs of two primary audiences: developers of circular-based architectural projects and stakeholders seeking to establish a circular regional territorial ecosystem. The latter group includes public bodies, administrations, and public–private partnerships that aim to promote the adoption of circular strategies at the regional level. In this sense, the range of stakeholders could be extensive, encompassing diverse expertise and requirements. The framework could serve as a tool providing a common language regarding specific themes and objectives for decision-makers (public administration); designers (professionals); those implementing circular practices (businesses); those connecting stakeholders and flows (ecosystem orchestrators); and those analyzing, disseminating knowledge, and developing indicators on these practices (research and training).

The planning and decision-making phase at the regional level, managed primarily by public actors, is essential for facilitating the transition of the built environment from a linear to a circular model [107]. Decisions made by public actors influence private developers and, consequently, how buildings are designed, constructed, used, and managed throughout their lifecycle [107]. To implement circularity strategies at the building level, consistent action is necessary from the earliest stages of the design process [77,108]. In this scenario, the ACT-FLOW Framework can provide guidance to public agencies and policymakers on how a territorial approach can support strategic planning and the coordination of a local circular territorial ecosystem. The systematic mapping of actors and flows within a local context can serve as a knowledge base for planning and contribute to the integration of circular practices into public procurement. One potential approach is to incorporate criteria in public procedures that incentivize the use of materials sourced from local reuse supply chains. In addition, it would be necessary to explore incentives for selective demolition; simplify procedures for the reuse of materials, components, and products; and develop tools to support the creation of infrastructure that facilitates the spread of such practices across the region. The application of the framework by local public administrations (provinces or regions) could also provide the basis for establishing permanent multi-stakeholder roundtables to facilitate cooperation and the exchange of information in support of the creation of local digital platforms for material traceability and the dissemination of the expertise necessary to implement cross-sectoral circular practices across multiple economic sectors.

Furthermore, the formation of a local circular economy ecosystem would facilitate the emergence of new organizational models, intermediary roles (e.g., professional salvage dealers, local hubs, recovery cooperatives, and reuse experts), and enhanced stakeholder integration (e.g., designers, demolition contractors, materials retailers, and digital platforms). This integration would enable the transition of business models towards service-based approaches (e.g., product-as-a-service, building-as-a-service, etc.). At the same time, a coordinated network of actors could also help mitigate the business risks associated with transitioning to business models more oriented towards circularity.

6.3. Reflections on Indicators

The framework employs indicators derived from recognized tools and implements them in a simplified manner. This simplification is crucial because it allows for easier application of the indicators using the data available during the preliminary design phase, which consists of a rough bill of quantities. It is essential that the quantitative values obtained from the indicator calculation be subjected to critical analysis in the project's early stages. This analysis will facilitate the identification of modifications and guide subsequent design phases in a more iterative manner, following a Plan–Do–Check–Act methodology [36].

For this reason, the circularity values reported here, both inflow and outflow, cannot be directly compared with the results of other projects. It is necessary to highlight that one critical issue regarding circularity is that there is no agreement on how to measure the circularity of certain products, such as buildings [13,14,109].

These values should be viewed as internal indicators useful for tracking the project's evolution toward higher circularity values in terms of both material procurement and end-of-life management. In fact, the use of indicators and the calculation of performance metrics facilitate tracking the project's transition from a linear to a circular model and monitoring its evolution over time [110]. Additionally, indicators can serve as a guide that directs the design process towards strategies that prioritize circularity [78].

Ingoing and outgoing circularity values enable a direct correlation among material stock, circular inflow, and circular outflow, providing a representative measure of the degree to which resource flows within the project exhibit a certain level of circularity. Under conditions of total circularity, the material inflow and outflow should match the circular inflow and outflow. It should be noted that, during the early design phase, the incoming material flow can be considered equal to the outgoing flow. In subsequent phases, however, additional secondary flows that could alter these two values should be considered. Examples include the outgoing flow of waste from the construction phase and the incoming flow of materials used for component repairs in the operational phase.

With a value of 238.17 kg/m^2, the material intensity is consistent with buildings constructed using lightweight steel and wood systems [5,111,112] and is lower than that of buildings with load-bearing concrete and brick structures [112,113]. Therefore, this value is associated with a relatively low inflow of materials. Regarding the CI value, the results indicate significant room for improvement in material selection, particularly for interior walls and exterior finishes, which are currently made of new materials. The CO value could also be improved by implementing technical solutions that promote the reuse of materials and components other than steel. The incoming (58.8%) and outgoing (70.2%) values should serve as baseline figures to verify that subsequent detailed design and construction decisions improve the project's overall circularity. These indicators, together with CI and CO, are dynamic and change in response to technical project-shaping decisions.

6.4. Validation of Framework and Its Limitations

The results of the validation questionnaire for the ACT-FLOW Framework provide an overall positive assessment against the criteria of the SMART approach, confirming the consistency of its components and its potential applicability in the construction sector. Across the panel, the framework received strongly positive support: 73.8% of all judgements were "Fully satisfied" and a further 24.5% "Partially satisfied", so that 98.4% of judgements were positive and only 1.6% (15 of 910) expressed dissatisfaction (Table 7). The overall mean score was 2.72 on the 1–3 scale (SD = 0.48), confirming a generally high level of agreement among respondents' opinions. At the level of individual components, mean scores ranged from 2.57 to 2.87. The narrowness of this range (0.30 points) indicates that no component was regarded as weak in absolute terms and that the framework was perceived as internally balanced.

Table 7. Expert evaluation of the ACT-FLOW components by SMART criterion, aggregation of the results (14 participants). Scores coded as Fully satisfied = 3, Partially satisfied = 2, Not satisfied = 1.

SMART Criterion	Mean (1–3)	Fully sat. %	Partially sat. %	Not sat. %
Specific	2.77	79%	19%	2%
Measurable	2.62	64%	33%	3%
Achievable	2.77	77%	22%	1%
Relevant	2.81	82%	17%	1%
Time-bound	2.64	66%	31%	2%
Overall	2.72	73.8%	24.5%	1.6%

Disaggregating the results, we see that the criterion with the highest score is "Relevant" (mean 2.81; 82% "Fully satisfied"), while the lowest score is assigned to "Time-bound" (mean 2.64; 66% "Fully satisfied") and "Measurable" (mean 2.62; 64% "Fully satisfied"). This result indicates that the experts strongly supported the relevance and feasibility of the strategies, while noting that their timeframes and measurability through the proposed indicators are already very good but could be improved.

The multi-level structure, which is divided into strategies, processes, and indicators, was recognized as an effective tool in supporting the definition of objectives and their operational implementation. This structure clarifies the relationships between the actors involved in circular processes at the territorial level. The open-ended responses confirm this interpretation, repeatedly highlighting the framework's ability to structure and highlight interactions between stakeholders. This is a particularly salient aspect in highly fragmented contexts. Concurrently, some issues have emerged. First, several respondents have noted a significant level of complexity, which is linked to terminology that is not always unambiguous and to incomplete definitions of certain operational components. Secondly, certain challenges have been identified, including the complexity of measuring and monitoring specific indicators over time, as shown by the results, and the need to adapt the framework to various local contexts.

A recurring theme across the three open-ended questions concerns operational applicability. In fact, the responses highlight some key aspects:

- The need to develop dedicated support tools, such as digital platforms, user-friendly interfaces, or operational guidelines;
- The need to simplify certain components of the framework, making them more accessible to users with varying levels of expertise;
- The importance of considering practical constraints relating to project timelines, available resources, and the capabilities of stakeholders involved.

Taken together, these indicators show that the favourable assessment of the framework was shared among participants rather than driven by a few highly positive respondents and that disagreement, where present, was concentrated on the "Measurable" and "Time-bound" dimensions identified above. These convergent quantitative and qualitative findings support the content validity of the ACT-FLOW Framework and delineate a clear agenda for its future refinement.

The primary constraint of this work is that the case study has not yet been concluded. This does not limit the usefulness of the framework, since, as previously mentioned, the tool proposed in this study is designed to support decision-making in the early stages of a project. However, this could limit the overall assessment of the effectiveness of the processes identified by the ACT-FLOW Framework. In this case, a completed and consolidated case study would allow for ex post analysis of circularity, investigating the relationship between identified processes and expected circularity outcomes.

One of the main limitations of the tool is its application to a single case study. This primarily affects the assessment of the effectiveness of the quantitative indicators. Applying the framework to more case studies would provide more data on the structure of the identified processes and, most importantly, on the ability of the indicators to monitor progress towards circularity. The collected data may allow for a comparative analysis of the values obtained from the various indicators. This could enable benchmarking and the establishment of quantifiable targets regarding the levels of circularity to be pursued in the design phase. While it may appear to limit the application of indicators, testing the framework on a single case study has actually enabled more effective testing and management of the stakeholder engagement and network-building processes presented in this paper. As we have seen, these processes are quite complex to initiate and manage; limiting the study to a single case significantly reduced the complexity involved.

Overall, these observations indicate that, despite a solid theoretical foundation, there is still room for improvement in the practical implementation of the framework, particularly in terms of usability, scalability, and transferability. In this context, the "Adjust and Iterate" phase plays a central role. It serves as an essential mechanism for ensuring the

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adaptability of the proposed model by systematically integrating stakeholder feedback. The application to the Circular Design Polito Lab validates the approach, emphasizing the potential of research infrastructures to serve as catalysts for collaborative networks and as experimental environments for testing and refining circular design models.

7. Conclusions and Future Developments

The objective of the present study was to understand how to facilitate the implementation of circularity strategies at the building scale by activating processes at the territorial level. To this end, a framework was developed to guide decisions during the planning and preliminary design phases of architectural projects, directing them towards the implementation of circularity principles and strategies.

The application of the ACT-FLOW Framework has demonstrated its effectiveness in activating stakeholder networks to support a project and improve decision-making during the intervention's planning phase. Furthermore, the framework has facilitated the implementation of operational procedures that effectively enable certain circularity strategies, such as material reuse and design for disassembly. Furthermore, the framework enables the integration of the meso-level dimension of circularity, defined by circular strategies and material procurement processes related to a specific architectural project, with the macro-level dimension, represented by the network of actors established within the local context in which the project is situated.

Designers and developers in the construction sector can adopt the framework as a tool for defining circularity objectives and the processes to achieve them. Using this framework to set up a construction project allows for careful consideration of circularity strategies and the most appropriate tools to engage and involve new partners from the earliest stages. This framework can also serve as a useful starting point for other researchers studying specific indicators related to stakeholder networks and engagement. Further research could evaluate the integration of additional indicators related to managing material flows.

Based on the findings outlined in this paper, three potential future research directions can be identified. First, the longitudinal application of the framework to the different stages of development of the Circular Design PoliTo Lab will allow observation of whether the ecosystem evolves from a network in which actors are formally included into one in which active synergies among them are effectively established. In this way, the results, which are currently preliminary, can be consolidated. A targeted survey of the stakeholders in the support network would help track this evolution. Second, the completion of the Circular Design Polito Lab will enable an ex post assessment of circularity to be compared with the ex ante results produced by the framework. This comparison may reveal elements to integrate into ACT-FLOW for performance monitoring across the entire project lifecycle. Third, a structured analysis, broader than the one outlined here, of the operational evaluation frameworks in the literature could clarify how ACT-FLOW, designed for the preliminary phase, relates to frameworks that rely on data available in later design phases, supporting the selection and application of qualitative and quantitative indicators and the definition of a process for monitoring the project's "circular" performance throughout all design phases and even during the use phase.

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Appendix A

Table A1. Summary table of the guidelines, regulations, and frameworks analyzed.

Name	Country (Year of Publication)	Selection Criteria	Synthetic Description	Elements Incorporated in ACT-FLOW F.	References
Guidelines FCRBE project	Northwestern Europe (2019)	It provides detailed guidelines to help professionals in the construction industry develop a reuse process.	The European FCRBE project is the result of research involving various public and private stakeholders and aims to significantly increase the reuse of building components in Northwestern Europe. The main objective is to increase reuse by 50% by 2032 by strengthening recovery supply chains, integrating reuse into design practices, and building a transnational ecosystem to support the circular economy in the construction sector. This project produces a package of technical documentation that introduces theoretical aspects of reuse and operational practices, and aims to significantly increase the reuse of building components in Northwest Europe	L2 Processes: - Procedures to be followed and tools used in the various stages of a material and component reuse process. - Stakeholders and their roles within the value chain. - Structure of data sheets for recovered components (Reclamation Audit) to facilitate their reuse. L3 Indicators: "Material" indicators for monitoring material flow.	[84]
DIN SPEC 91484	Germany (2023)	It provides a standardized procedure for the recovery of materials from selective demolition	The DIN SPEC 91484 standard was developed in collaboration between the German standards organization DIN, the consulting firm Concular, and other local companies. This standard establishes operational procedures to define a standardized process that supports the assessment and circular management of building materials and components, facilitating their identification, documentation, and reuse prior to demolition or renovation.	L2 Processes: Procedures to be followed and tools used in the initial stages of acquiring materials or components for inclusion in a reuse process.	[82]
AGEC Law	France (2020)	It provides a standardized process that facilitates circular practices at decommissioning sites	The AGEC Law (Anti-Gaspillage pour une Économie Circulaire, February 2020), or the "Anti-Waste for a Circular Economy" Law, stipulates that all products selected on site (at the decommissioning site) by a "qualified reclaimer" shall not be considered waste, but rather new raw materials that can be put back into circulation.	L1 Strategies: Define a legal distinction between reuse (legal, not derived from waste) and recycling (derived from waste), to avoid the imposition of restrictions and liabilities arising from 'waste status'. L2 Processes: Define an on-site sorting (in situ triage) carried out by qualified professionals. Prohibition on the transfer of materials intended for reuse via waste disposal centers.	[83]
Level(s) framework	European Union (2021)	It provides guidance on procedures and strategies to achieve specific environmental performance goals.	Level(s) is a framework developed by the European Union that provides a set of indicators to help professionals and organizations in the construction sector measure, assess, and improve the environmental performance of buildings throughout their entire lifecycle. Among the various environmental objectives it promotes is the development of efficient and circular lifecycles for materials and resources.	L1 Strategies: Use of tabular checklists L3 Indicators: Indicators, based on a dimensionless score, to measure adaptability and dismantling	[89]
Circular transition Indicators	International (2025)	It provides indicators that assess inflows and outflows, as well as current and potential recovery	The report identifies metrics for each stage of the building's lifecycle (design, construction, and operation) to assess and improve its circular performance.	L3 Indicators: Indicators for material flow management and circular design, divided by stage of the lifecycle	[87]

Criterion Dgnb–TEC 1.6–Circular Construction	Germany (2023)	Provides indicators for building circularity indices	This criterion, which is part of the DGNB New Construction certification scheme, aims to improve material efficiency in the construction of new buildings. To assess certain indicators, the criterion introduces calculation methods for quantifying a building's circularity.	L3 Indicators: Indicators for assessing circularity in building design and end-of-life	[88]

Table A2. Table of qualitative and quantitative indicators.

ID	Name	Correlated Process	Calculation Method	Description	Unit	Reference
QL1	Territorial consistency of the network	Stakeholder network	Qualitative assessment of ecosystem types and their spatial scale	Assess the type of governance in place and the geographical scope of the ecosystem	Textual description	[85,102]
QT2	Number of active members in the network for each category involved		Number of active members in each category (company, public agency, etc.)	Measures the size and evolution of the network over time	Dimensionless number	[102]
SQT3	Geographical distribution of stakeholders in relation to the project site		Calculation of the distance (km) between each stakeholder and the project site (0–20 km = local; 21–60 km = regional; >60 km = multi-regional)	Analyze the network's geographical proximity	Kilometric range	[46,102,104]
QL4	Existence of structured moments to co-define values and CE vision	Stakeholder engagement activities	Yes/No + description of the activities used (workshops, seminars, etc.)	Assess the presence of participatory governance practices in the network (workshops, events, seminars, etc.).	Textual description	[85]
QT5	Number of activities, participants and organizations involved		Number of completed activities and participants	Measures the intensity of interactions and network activation	Dimensionless number	[85,102]
SQT6	Diversity of active stakeholders		Number of categories involved (company public agency, etc.) and level of involvement (1 = informational, 2 = consultative, 3 = collaborative).	Assess the extent and intensity of participation in the network	Composite index	[85,102]
QT7	Material stock and Material intensity	Management of material flows	$MS = \sum(\text{functional unit}_i \times \text{Material Intensity}_i)$ MI_i = Material Stock/functional unit	MS_i for single materials is extracted from the bill of materials. Provides guidance on the quantity and type of materials to be used in the project	Kg Kg/mq	[5,114,115]
QT8	Circular Inflow		$CI = \sum(MS_i \times fCI_i)$ where MS_i is the mass of the material stock for the various types of material, and fCI_i is a factor used to assess circularity classes	Assess the circularity of the supply chain for the materials to be used in the project. The purpose of using this indicator is to assess the potential of the region as a source of 'circular' materials.	Kg	[88]
QT9	Circular outflow		$CO = \sum(MS_i \times fCO_i)$ where MS_i is the mass of the material stock for the various types of material, whilst fCO_i is the Circularity Coefficient, the values of which are shown in the table below.	Assess the circularity of the end-of-life cycle of the materials to be used in the project. The purpose of this indicator is to evaluate the best technological solutions for preserving the integrity of the material in order to facilitate its future reuse.	Kg	[89]

Table A3. Tablet format for the determination of circular strategies (Level 1).

Definition of the Objective of the Project	Individuation of Circular Strategies	Key Strengths for the Implementation Process
1 The creation of an innovative research and teaching infrastructure that becomes, in itself, a "manifesto" of circular practices. 2 The activation of networks of actors to support the laboratory's activities and the implementation and development of a circular territorial ecosystem that takes a broad view of the 10R framework, expanding on the Rs currently implemented. 3 The need to make the building easily adaptable to new spatial configurations, to ensure its reconfiguration and expansion over time.	☐ Dematerialization ☐ Diversity of materials used ☑ DfD ☐ Design for product maintenance ☐ Design for adaptability ☐ Durability ☐ Design for modularity ☐ Design for recycling ☐ Design for remanufacturing ☐ Design for reuse ☐ Design to improve the production ☐ Standardization ☐ Eco-fusion ☐ Green public procurement ☐ Improved energy efficiency ☐ Passive-house design ☐ Product service system ☐ Recycling ☐ Regenerative design ☑ Reuse of materials ☑ Network-based or collaborative relationships ☐ Study solutions for transport ☐ Studying alternatives ☐ Decarbonization of supply chain	Involvement of local companies with expertise in decommissioning Involvement of public and private actors already part of the ECO3R ecosystem Identification of new companies supplying "circular" materials Use of know-how already present within the university

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