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Circular and Adaptive Transformation of the Housing Stock towards a Regenerative Future

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Abstract: The transition from a linear economy to a CE (circular economy) has the potential to reduce resource use, environmental impacts, and waste in the built environment. Creating a CE in the built environment is therefore of fundamental importance to achieve a sustainable society. Through the application of a systemic approach that considers the building as a set of technological subsystems (e.g. vertical closures, roof, furniture, etc.), components (e.g. infill panels), and materials, this paper—starting from a review of the literature on the topic of the CE applied to construction—establishes a framework of circular design strategies and definitions that link the VRPs (value retention processes) framework, based on the R-imperatives, to the Design-for-X strategies. The first research objective is to develop a design tool for circular building components and technological subsystems.

Key words: Adaptability, sustainability, circular transition, regeneration, remanufacturing.

1. Circular and Adaptive Model for a Regenerative Built Environment

The urgency of reflecting on the concept of "regeneration" is increasing, especially considering that the construction sector is the largest consumer of resources and exerts the greatest pressure on the environment [1]. This sector is responsible for 40% of global material consumption and 40% of global waste [2], and approximately 38% of all human-induced CO_2 emissions, of which 10% can be attributed to the production of materials needed to build, maintain, and renew the built environment [3]. Considering the projected global population growth to 9.6 billion by 2050 [4] and the resulting increase in the use of materials in the built environment [5], a different approach will be necessary to construct, maintain, and renovate future buildings. This objective is shared by EU (European Union) and national policies (the decarbonisation and renewal of the existing housing stock envisaged by the EU's Next Generation Programme and in Italy, by the PNRR (National Recovery and Resilience Plan), the PINQuA—National Innovative Programme for Housing Quality; the Energy Communities introduced by the European Commission, etc.) that have long been attentive to direct both urban settlements towards a condition of balance with the environment and the health and well-being of its inhabitants and the "housing market" towards forms of "housing as a service", considering the home as a "complex system" that must provide in a single "package" different and variable performance requirements: building, common spaces, furnishing systems, technical/plant solutions with a high technological content and low maintenance/management, etc.

Two issues emerge from this perspective. The first concerns the housing stock of the main European centres. The housing stock is made up of dwellings inherited from the past that require "permanence"—through actions of restoration/maintenance of acceptable performance conditions—and at the same time "change"—through solutions adapted to the demand for temporariness of location and use. Two positions and approaches to regeneration correspond to this demand.

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- the exclusive regeneration of the city's physical resources with Performance Based Design actions, at the scale of the building and the efficiency of its construction elements (LCA, UNI/EN-ISO standards, LEED, BREEAM, ITACA certifications) through a top-down process of applying design solutions that meet universal performance standards;
- the induced regeneration in the human and social resources of the urban environment based on user-centred approaches (Universal Design, Design for All, Participative Design, Flexible Design) that recognise the user as an active participant through a bottom-up process that emphasises holistic engagement, collaboration and provides customised technical solutions [6].

This condition directs the regeneration policies of the residential stock towards interventions on single themes (energy, safety, climate change, sustainable building, health) or dedicated to specific categories of users and their exclusive areas of competence (housing for families with children, for elderly people, for disabled people, for tourists). However, it is precisely in the urban context—in which, more than elsewhere, every single fragility is related to the "whole" and every single action produces an echo or a cascading effect on the well-being of users and the health of the planet—that new solutions and rules for the regeneration of the residential heritage are needed, no longer as a summation of technical interventions but as a process of technological reconnection between resources, spaces/objects and inhabitants [7]. According to this approach, regeneration seeks to have a continuous net positive impact on the environment, health, society, and the economy [8, 9] by actively reversing past damage through renewal, nurturing the ecosystem, and enhancing well-being ("more good"). The aim of regeneration is to reactivate a connection between inhabitants and habitat by actively restoring or revitalising ecosystems, improving biodiversity, and promoting environmental and community well-being [10].

The second issue concerns the evolution of the concept of regeneration of residential settlements as an adaptive process to the problems of eco-systemic, social and economic vulnerability. This convergence (regeneration-adaptation) entails, more than ever, the need for the concept of regeneration—which tends, virtuously, towards integrated ecological, social and economic quality [11]—to be redefined as a "dynamic boundary". In this sense, regeneration should generate products that are not "disposable" but "error-friendly" or "predisposed towards error" [12] and structured to "regenerate" following damage or decompensation through actions of transformation, repair, maintenance, reuse, reconditioning, etc. Thus, a further meaning of regeneration is the valorisation of the reciprocal link between the adaptation/evolution of people/habitats and the intensity of stresses induced by the environmental, economic and social context.

A paradigm shift is needed in the interpretation of the "regenerative process", seen not only as a solution for the restoration/maintenance of acceptable performance conditions—in a linear vision of the life cycle of the designed system—but a moment of "reset/restart" in which the action (of transformability, maintainability, replaceability, reversibility, mitigation/compensation, etc.) underlies a set of strategies structured in a circular process (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover) [13]. In this sense, interventions on the built environment constitute an opportunity to lead cities towards an ecological transition, if considered both as adaptive actions of external vulnerabilities (environmental, social and economic) and internal ones (variability linked to user needs) but also as interferences (of circular micro-processes) to the linear process with which cities have been conceived and evolved, to constitute a step towards the creation of a potentially regenerative and resilient built environment.

Responding to these challenges requires the adoption of technological and typological principles capable of accommodating change in order to increase the life of the home—Life Cycle Design—understood as the sum of several cycles of use by users with different needs and reducing its environmental impact.

This paper is part of this framework and returns a multifaceted research activity aimed at further exploring the implications that exist between the need for adaptive regeneration to guarantee adequate levels of performance and functionality for the urban space, the building and its every component/material and the equally urgent need for environmental sustainability. Starting from a collection and systematization of literature and case studies on the theme of building stock regeneration, the paper proposes a redevelopment/regeneration model of regeneration of residential buildings based on a framework of adaptive/circular strategies on the different scales (components and buildings).

2. Open Loops vs. Closed Loops

There is no consensus on the definition of CE (circular economy). Kirchherr et al. [13] conclude that there are more than 114 definitions of the CE in use. The concept of CE evolves around the idea of building cyclical flows to keep resources in use for as long as possible and at their highest utility and value [14] so that the concept of waste is eliminated [15]. Following the definition of Geissdoerfer et al. [16], we understand CE as a regenerative system in which resource input and waste, emissions, and energy leakage are minimized by "slowing", "closing", and "narrowing" material and energy loops (Fig. 1).

The basic strategies of narrowing, slowing and closing cycles were introduced by Bocken et al. [17] and can be summarised as follows:

- "narrowing loops" is to reduce resource use per product, or achieve resource efficiency, according to this approach the design of lightweight components or the use of non-virgin, bio-based, or low-impact materials can support "narrowing loops";
- "slowing loops" is to slow down the flow of resources through extension or intensification of the utilization period, i.e. service loops to extend a product's life, for instance through repair, remanufacturing, or the modular design, size standardisation and the application of demountable joints can support "slowing loops" by facilitating repair, reuse and future adjustments;
- "closing loops" refers to the process of recycling materials, which allows for a circular flow of resources between post-use and production, i.e. the application of recyclable or biodegradable materials that can be separated during end-of-life products can support future "closing loops".

Various authors have provided circular design strategies that can support "narrowing", "slowing" and "closing loops" [18, 19] through VRPs (value retention processes), or R-imperatives [20-22]. Central to a CE is a range of circularity strategies, also known as value retention options or principles, typically grouped within different R frameworks. These frameworks range from the 3Rs of "reduce, reuse, and recycle" up to the 10Rs of "refuse, reduce, reuse, repair, refurbish, remanufacture,

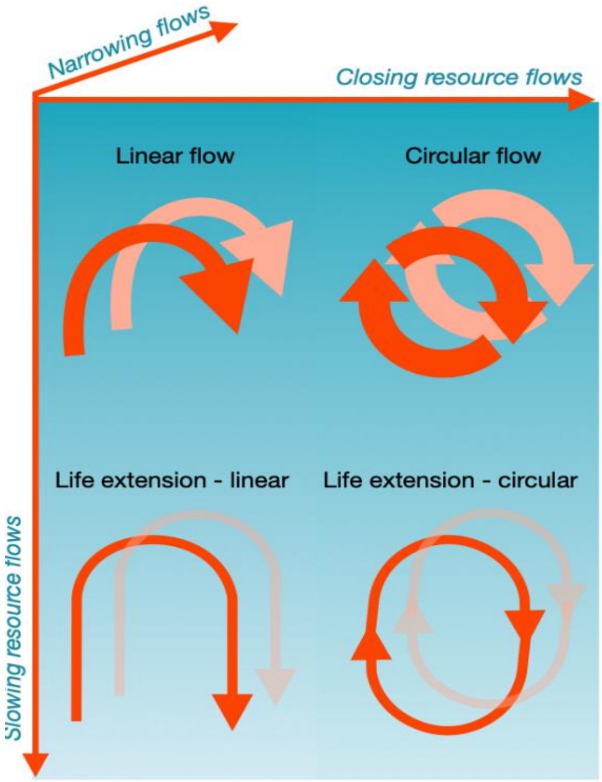


Fig. 1 Narrowing, slowing and closing the loop framework. Image adapted from Bocken et al. [17].

repurpose, recycle, recover, and remine" [21]. These value retention options are not necessarily exclusive and can be used in parallel or combined to narrow, slow, or close resource loops [17].

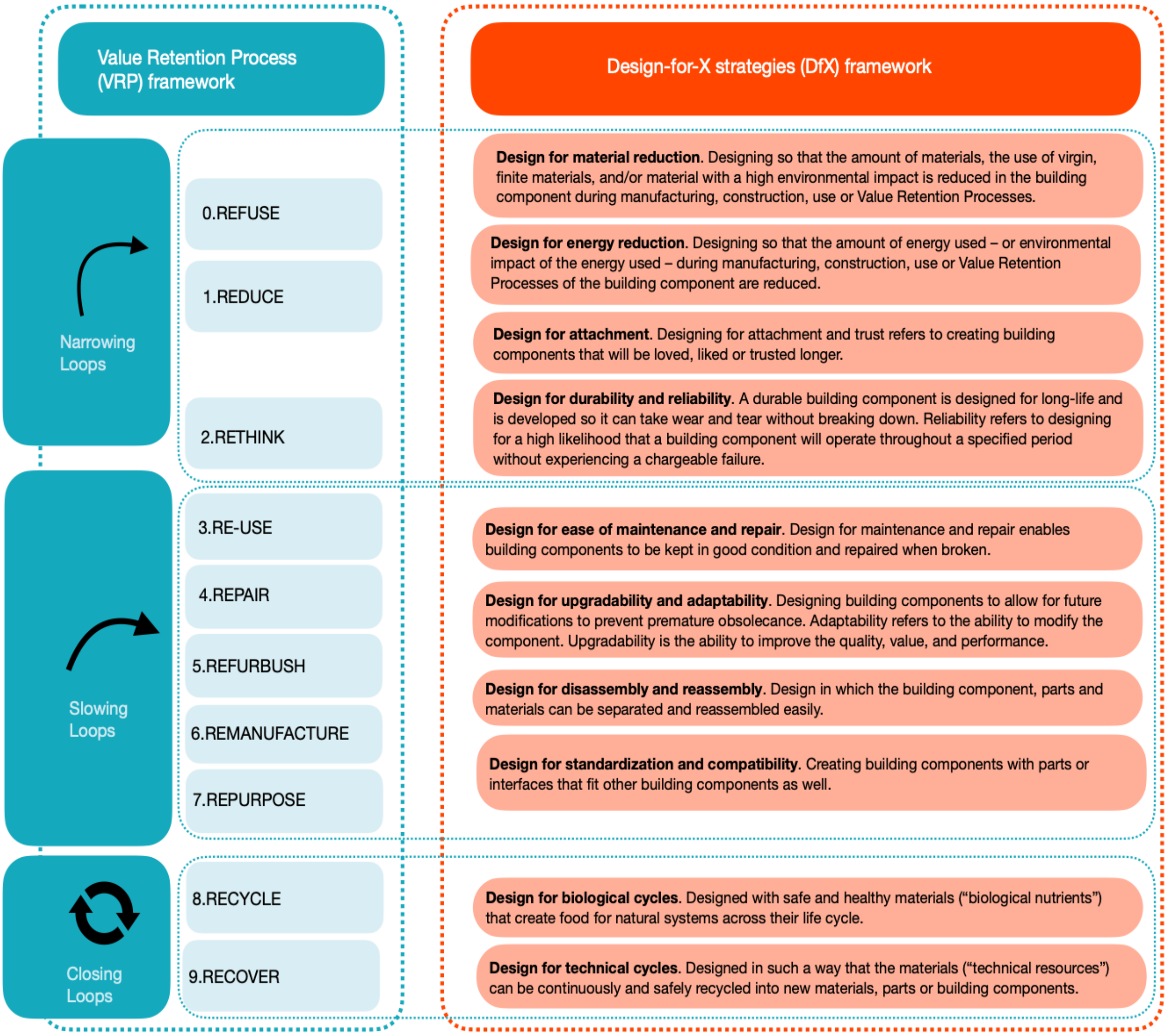
However, the regeneration of the built environment is not limited to biological and ecological approaches, but goes beyond environmental considerations by offering design and construction practices that recognise the collaborative role of the user and enable the generation of economic and social environmental benefits. This perspective of regeneration is the basis for design practices known as DfX (Design for X) strategies. Examples of DfX are "Design for Recycling" and "Design for Disassembly". These approaches are developed by some authors with circular design options [18, 23]. These options can be traced back to building components. Based on these assumptions, the initial outcome of the research was to establish a framework of circular design strategies and definitions that links the VRP framework, based on the R-imperatives, to the DfX strategies (Fig. 2).

3. Systemic Approach for the Regeneration of Buildings and Components

The circular regeneration operates across multiple implementation scales, from the micro (products, component) to meso (buildings, eco-industrial parks) and macro (cities, built environment) scales. Focusing, in this paper, on the building stock, the realisation of a circular regeneration requires a "system approach" that considers the building as a set of technological subsystems (e.g. vertical closures, roof, furniture, etc.), components (e.g. infill panels), and materials during all phases of the building's operation in order to maintain the cycle of resources at maximum utility and value [17, 24]. Several studies have attempted to break down the designed space into layers to investigate the durability of individual parts. Examples in this sense are: the studies of Duffy [25] who divides the building into four layers called Shell, Services, Scenery (setting in which the action takes place) and Set; the experiences of Brandt [26] who draws a similar system of categories, and divides the building into Site, Structure, Skin, Service, Space Plan and Stuff, according to the capacity for permanence or the speed of change and replacement to which they are subjected during the building's life cycle. Habraken [7] also distinguishes six built environment hierarchies, considering the street network, building, partitions, furniture, body and tools. These studies show how each layer can be further subdivided into technical components/elements and materials with their own life and durability characteristics that have effects on the entire design system, from the supranational to the material scale (technical model). Although the research focuses on building and building component design, the systems approach compels the designer to consider the cycles of each part of the building system in cohesion. This prevents any element from becoming a "weak link" that could cause premature obsolescence of a larger part of the building system or even the entire system.

The factors that influence the cycles of the technical building decomposition model are external and internal factors. External factors such as industrial and business models can incentivise circularity. For instance, if the business model makes it more cost-effective to purchase new components, parts, or materials for a building, repairing them becomes less likely. Bocken et al. [17] suggest that, in addition to the design of the business and design models, the supply chain or industry model should also be taken into account. Internal factors, such as the variability of users' housing needs (e.g. variability of the needs of the family unit over time, of the number of users and of socio-emotional relationships; variability of the use of space which determines the functional obsolescence of housing systems of inherited assets) can benefit from technical systems that allow easy reconfiguration of the living space.

In recent years, scientific literature itself has paid attention to "designed systems" as open, easily updatable systems, to adapt their performance to renewed demand frameworks.



Design for material reduction. Designing so that the amount of materials, the use of virgin, finite materials, and/or material with a high environmental impact is reduced in the building component during manufacturing, construction, use or Value Retention Processes.

Design for energy reduction. Designing so that the amount of energy used – or environmental impact of the energy used – during manufacturing, construction, use or Value Retention Processes of the building component are reduced.

Design for attachment. Designing for attachment and trust refers to creating building components that will be loved, liked or trusted longer.

Design for durability and reliability. A durable building component is designed for long-life and is developed so it can take wear and tear without breaking down. Reliability refers to designing for a high likelihood that a building component will operate throughout a specified period without experiencing a chargeable failure.

Design for ease of maintenance and repair. Design for maintenance and repair enables building components to be kept in good condition and repaired when broken.

Design for upgradability and adaptability. Designing building components to allow for future modifications to prevent premature obsolecance. Adaptability refers to the ability to modify the component. Upgradability is the ability to improve the quality, value, and performance.

Design for disassembly and reassembly. Design in which the building component, parts and materials can be separated and reassembled easily.

Design for standardization and compatibility. Creating building components with parts or interfaces that fit other building components as well.

Design for biological cycles. Designed with safe and healthy materials ("biological nutrients") that create food for natural systems across their life cycle.

Design for technical cycles. Designed in such a way that the materials ("technical resources") can be continuously and safely recycled into new materials, parts or building components.

Fig. 2 Circular design strategies related to the VRP and DfX frameworks.

4. Strategies to Increase the Remanufacturing Potential of the Housing Stock

The review of the literature on the regeneration process in a circular key led to the identification of different strategies, which proceed by successive approximations between an external horizon (the relationships of the designed system with its constituent parts and with its contextual environment) and an internal horizon (all its determinations in relation to user), classifiable with respect to the following levels: material/component level and technological subsystem level (Fig. 3).

4.1 Materials Up-Cycled, Healthy and Reactive

This level is characterized by actions aimed at choosing materials and assembly systems capable of giving products adaptive behavior through the reactivity of the technical elements of which they are made with respect to the variability of external stresses (environmental vulnerability) and/or internal ones (variability of users' needs). This level poses two challenges for the project.

The first concerns the relationship between the material dimension and the project which evaluates the component no longer only from the point of view of

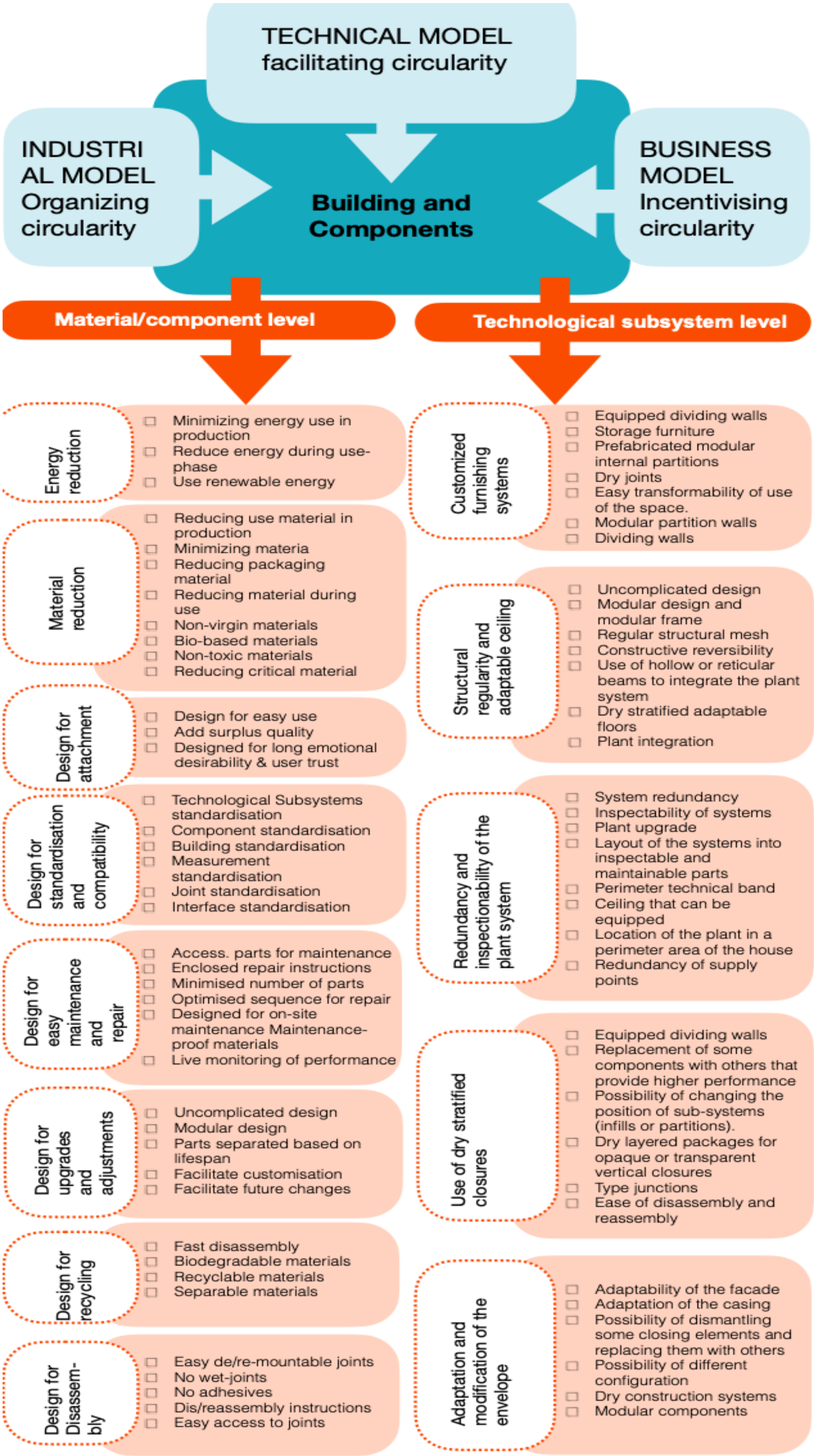


Fig. 3 Selection of some of the circular strategies identified.

the technical and environmental performance linked to the contingent situation, but also to the ability to react to stress. Research conducted in recent years regarding materials is emblematic: from bio-based materials inspired by biological systems (biodegradable, compostable, recyclable) with "resilient capacities" in terms of optimization of the production process concerning consumption of resources and the impacts produced [27], to react-based ones integrated with nanotechnologies functional to activation of self-regulation processes (Phase Change Material) which reduce the dependence on external maintenance/energy sources. Examples include enclosures made of self-cleaning or self-repairing materials, such as the "lime clasts" of pantheon concrete, which give the concrete self-healing properties [28] or the innovative application of "mycelium"—used in the Belgian pavilion at the 18th Venice Architecture Biennale—as a regenerative building material, which is kept alive so that walls can self-repair [29]. Depending on the objectives to be achieved, the interventions can refer to single parts or the entire building and structured according to a Circular Supply Chain Management approach [30]. High- and low-tech products also fall into this category. High-tech plant-based products are those that improve energy efficiency, enhancing insulation and aesthetics [31], materials that capture greenhouse gas emissions from the air or absorb renewable energy at the community level, promoting self-sufficiency, the well-being of the natural environment and its inhabitants.

Low-tech "upcycling" solutions concern the transformation of waste materials that go beyond the C&D waste within the construction sector to encompass cross-sectoral symbioses, exchanging waste materials across sectors. Transforming waste materials into low-cost housing solutions promotes improved waste management that may reduce the use of non-renewable virgin materials [32-34]. Examples are bricks from plastic bottles, roof, ceiling or wall panels from agricultural waste or chopped cane, insulation or other building materials from household waste, or facade plates made of recycled materials.

The second challenge concerns the relationship between the constructive system and the project and transfer to the building industry of the logic of design for disassembling, by now widely tested in many industrial sectors and long since theorized and tested in industrial design [12], which affect adaptability to external/internal stresses in terms of ease of maintenance, disassembly, and repairability.

In support of these actions, activation of innovative business models that consider new types of relationships/exchange of materials/components between different operators is crucial, through collaboration networks (loop economy, industrial ecology, industrial symbiosis processes), sharing economy and digital platforms (harvest maps, product-service systems, re-manufacturing platforms) and methodologies such as Design for Manufacture and Assembly, Design for Deconstruction or Disassembly, which facilitate the recoverability, reusability, re-conditionability and recyclability of materials that have reached the end of their lifespan and of production waste [35].

Computer-aided fabrication, BIM (building information modelling), and systematic documentation of building details through, particularly, material passports (digital data sets containing useful information about materials, products, and buildings) have also become essential instruments for increasing the potential of future housing stock for reuse [10].

4.2 Housing Adaptable to the Evolution of Users/Habitats

This level concerns the building and its functional/architectural dimension and is characterized by actions aimed at increasing the life of the building product through recycling solutions of residential housing stock in terms of adaptive customization, i.e. personalization of spaces, equipment, furnishings and plant elements through a continuous upgrade/downgrade cycle. It follows that the value of the built space loses its centrality as an unchangeable artifact capable of responding to standardized needs necessarily limited to the short/medium term, to take on value from the ability to guarantee progressive adaptations and spatial and technological performance evolutions in the long term. Implementation of adaptability can be expressed on the scale of the building through spatial and technological options that consider the relationships of the requirements relating to the morphological-distributive characteristics (versatility, convertibility of space, evolution, expandability, extensibility), to plant and construction integrability (reversibility of partition/furniture systems in a logic of maintainability, disassembly, modularity/composability) with the sub-requisites of circularity relating to products/components (Refuse, Rethink, Reduce), to regenerative processes (Reuse, Repair, Refurbish, Remanufacture, Repurpose) and smart applications (Recycle, Recover).

At the level of the building, three spheres of application of the regenerative process can be identified. The first sphere concerns the regeneration of the housing space/furniture system. Regeneration is associated with solutions capable of conferring high internal transformability without modifying the overall volume of the building through the provision of spaces intended for different functions over time such as the organisation of the dwelling by a sequence of generic spaces [36]; the use of furnishing systems contained in equipped technical bands or in technical cores (fixed or mobile) within minimum multifunctional spaces; the provision of home automation solutions for the diversified use of small spaces and to compensate for the loss of abilities in frail and elderly people.

The second area of focus concerns the regeneration of the technological and plant systems of the dwelling. In this context, it is possible to identify solutions that allow for the transformability of the dwelling through the use of innovative construction solutions and components that replace the traditionally fixed parts of the building (partition walls, curtain walls, systems) with systems or kits of lightweight, semi-prefabricated or prefabricated components, pre-assembled or to be assembled in situ. Some solutions entail the addition or subtraction of prefabricated modules and the provision of plant cores that can be easily replaced with new technical components at a low cost and in a short time.

The third area of interest concerns the regeneration of the building envelope through additional operations. These may involve the addition of new functionalities to facades and roofs for the provision of additional services to users and potentially to neighbourhood communities [37]. Such functionalities can integrate special housing solutions with nature-based solutions for rain and wastewater treatment, biogas generation and in-vessel composting, thermal and photovoltaic systems for energy improvement, and green walls for air purification and home-level food production, and lead to the attainment of a nZEB (near-zero energy building).

The proposed functionality could be offered as a service to the community by facilitating circular business opportunities through forms of collaboration and co-creation. Potential additions may include the twinning of volumes on the envelope of the building to create building façades, or uniform/homogeneous growth of the building perimeter. The latter solution entails static, seismic and energy upgrading—where necessary—of the building and the formation of a continuous loggia along its perimeter. This allows for the extension of the internal surface area of residential units, thereby increasing the overall living space. The challenge is not only to achieve a balance between energy performance, environmental impact, and healthy indoor climate [38], but also to facilitate the active involvement of the user in controlling the components of possible short-term configurations within a fixed long-term support. This approach aims to facilitate the activation of multiple cycles of use of the dwelling and consequently to prolong its lifespan.

5. Conclusions

The main barriers to the implementation of the interpretative model are: technical barriers related to the rigidity of construction processes, which, in order to implement circularity strategies, should be rethought and oriented towards new business models and new relationships between actors interacting along the process and in the management of material flows; regulatory barriers that are excessively rigid and cumbersome, leaving no margin for creativity and design invention. Although the identification of different layers of strategies has the limit of a literature review conducted through databases (which could have led to the exclusion of relevant contributions and solutions), the results suggest promising research areas and multiple operational scenarios of use: as a support tool for the Public Administration to direct sustainable regeneration/ redevelopment interventions of existing buildings, and as guidelines in the drafting of innovative tenders for the regeneration of suburbs or for implementation of projects that can be financed under European programs.

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