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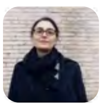

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Due to climatic, social, and epidemiological challenges, urban areas are suffering from recurring problems that require profound and sustainable solutions. Although they cover only a small area of the earth's surface, metropolises are responsible for most of the world's global carbon emissions, which cause adverse effects on energy and the climate. This book discusses the spatial development of ur...

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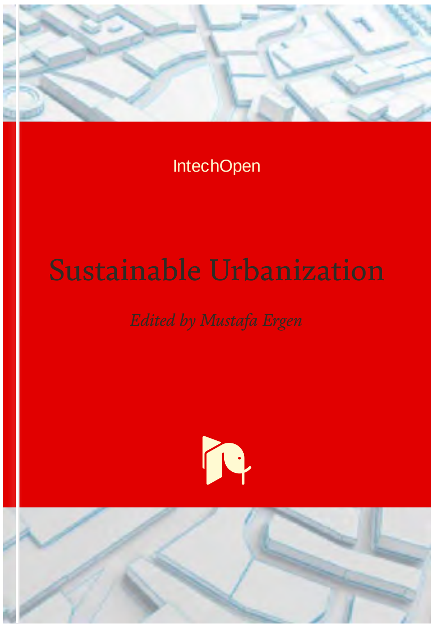

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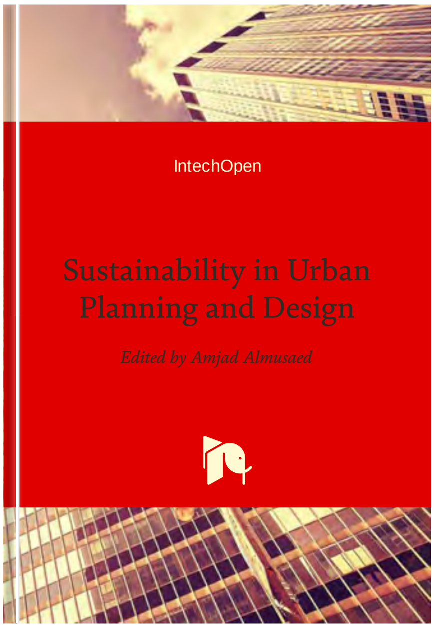

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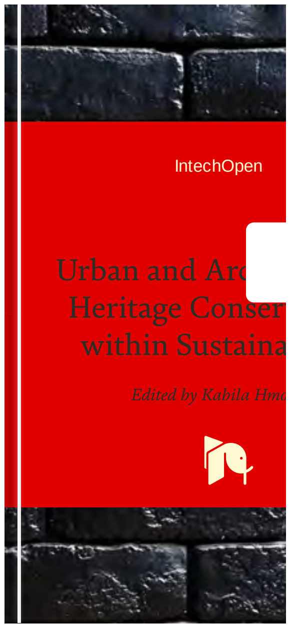

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Chapter

Reusable Cities: A Circular Design Approach to Urban Regeneration through Materials Reuse

Serena Baiani and Paola Altamura

Abstract

The "circular city" reduces its environmental impacts from many points of view: from construction-related CO_2 emissions to energy production. The key areas for the implementation of an "urban policy for transition" are mainly oriented toward the reuse and recycling of materials from the building processes and urban value chains (urban mining), also through reuse practices of the existing building stock. The results of the research activities, reported in the present contribution, demonstrate the possibility of integrating studies on the environmental benefits of recycling in the building sector, with investigations on the potential of reuse to increase the overall eco-effectiveness of building interventions, interpreting the urban built environment in the perspective of a "reusable city." The hypothesis for a real reduction of raw material consumption in the construction sector is to combine the use of secondary materials with the reuse of building components, resulting from partial or total deconstruction and of materials from other waste streams, not belonging to the construction sector. Therefore, the research sought to understand to what extent the reuse of architectural components and waste materials from other industries can contribute to increasing resource efficiency at the local scale, reducing the consumption of materials, land, and energy.

Keywords: circular cities, urban mining, reuse, building materials, Harvest Map

1. Introduction

1.1 Circularity and climate neutrality: the role of cities

"Rapid urbanization and increased consumption have led to economic growth in many parts of the world, but have also created unprecedented amounts of waste" [1]. The linear economy paradigm, the so called "buy-use-dispose" model, as adopted globally in particular in cities, is no longer sustainable, especially because of the growing production of waste, which is becoming unmanageable in many contexts. The UN Agenda 2030 [2], in fact, within Goal 12 of the Sustainable Development Goals, "Ensuring sustainable consumption and growth patterns," calls for significant waste prevention, reduction, recycling, and reuse by 2030. As the demand for natural resources is constantly increasing along with waste production, circular economy and material resource efficiency represent the only approaches that can help to face the challenge of decoupling growth from resource consumption, tackling the "dual issue of increasing waste and decreasing resources by incentivizing actors throughout the value chain to extract maximum use from both existing products and the elements within them" [1].

Implementing the circular approach means reconfiguring all material flows within the city (building materials, water, solid waste, electronic waste, and even heat and energy), in order to avoid waste. Urban areas, in this perspective, represent an ideal environment to implement circular economy, starting from the resources embodied in the built environment and in particular in the existing building stock. Cities around the world are already moving in this direction, experimenting actions and interventions to promote interactions among different value chains and stakeholders, which can effectively foster circularity, urban mining, and sharing economy. This the case for Montevideo, for instance, where less than 2% of the solid urban waste goes to landfill via the waste collection system and, thanks to the support of ARUP, circular economy is being implemented as a strategic approach to enhance the city's resilience [3].

Indeed, cities play a central role in the transition toward sustainability and circular economy: urban agglomerations contribute significantly to climate change and the overexploitation of resources, with impacts including land use, soil consumption, pollutants due to mobility, water and energy consumption, air quality, waste. Nevertheless, with their high concentration of resources, people, capital, data, cities offer excellent chances for cross-collaboration between all key actors (individuals, companies, government, civil society, research, etc.) that to take action and "lead to a more sustainable and livable future for the next generation of urban dwellers" [1].

In fact, as stated in 2020 by the European Commission in the updated Circular Economy Action Plan [4], circularity is a prerequisite for climate neutrality, having an important impact on climate change mitigation and adaptation and on greenhouse gas emission reduction, through carbon removal. Actions can be nature-based, including through restoration of ecosystems, forest protection, afforestation, sustainable forest management, and carbon farming sequestration, or based on increased circularity, for instance, through long-term storage in wood construction, reuse, and storage of carbon in products such as mineralization in building materials.

1.2 A vision of a circular city

Transitioning to circular cities entails defining a vision. According to the Ellen MacArthur Foundation [5], a circular city embeds the principles of a circular economy across all of its functions, establishing an urban system that is regenerative and restorative by design. In such a city, the idea of waste is eliminated, with assets kept at their highest levels of utility at all times and the use of digital technologies a vital process enabler. A circular city aims to generate prosperity and economic resilience for itself and its citizens, while decoupling value creation from the consumption of finite resources [6]. Amsterdam, one of the leader cities in the application of circular economy concepts to city governance, follows seven principles in its transition toward a circular economy, as elaborated in a report commissioned by the city government [7]:

- Closed loop: all materials enter into an infinite cycle (technical or biological).
- Reduced emissions: all energy comes from renewable sources.
- Value generation: resources are used to generate (financial or other) value.

- Modular and flexible design of products and production chains increases adaptability of systems.

- Innovative business models: new business models for production, distribution, and consumption enable the shift from possession of goods to (use of) services.

- Region-oriented reverse logistics: logistics systems shift to a more region-oriented service with reverse logistics capabilities.

- Natural systems upgradation: human activities positively contribute to ecosystems, ecosystem services, and the reconstruction of "natural capital."

The abovementioned principles can be extended to define a vision and an action roadmap for circularity in cities.

The "circular city" reduces its environmental impacts from many points of view: from construction-related CO_2 emissions to energy production. In the construction sector, a circular city would allow a 10-fold reduction in CO_2 emissions and a 75% reduction in soil consumption, with a 30–50% saving in construction costs. Circular construction allows the saving of natural resources, considering that the building and infrastructure sector consumes 1/3 of the world's raw materials, releases 11% of global emissions, and produces 40% of municipal solid waste within demolition processes. It is to be considered that the use of recycled building materials would reduce CO_2 emissions by 40–70% [8].

At the global level, the building sector is in fact a crucial one for the implementation of circular strategies, as demonstrated by the survey on the status of the circular economy in 34 cities and regions documented in the Report "The Circular Economy in Cities and Regions" by the OECD [9], where 61% of involved cities and regions declared to have a circular economy initiative including buildings (**Figure 1**).

Planning and design of urban areas and buildings should draw inspiration from the circular processes that occur in nature, by promoting a closed-loop use of resources, and therefore defining flexible, multipurpose spaces, using reused/recycled and recyclable materials, designing for deconstruction, so as to prevent the production of waste. In fact, in order to successfully deal with the problematic disposal of residues, the very concept of waste must be erased from our design and technological point of view [10], a new circular approach to the design, production, and procurement of materials has to be defined, with the involvement of all the stakeholders, including industry and waste operators.

By resorting to these processes, reproduced in an industrial key, and exploiting the synergy between urban and periurban areas (preferably industrial, to be redeveloped), it is possible to reduce the energy and environmental impact of these areas, rebalancing the impacts of cities.

From the point of view of territorial and urban policies, cities and regions are putting into practice a multiplicity of experimentations of systems and technologies for saving, reusing, and recycling. However, these are largely sectoral practices, still far from the adoption of integrated management and programming models for functions. This integration will increasingly have to bring the various phases of production and management of material and energy flows into coherence and coordinate the activities of the various territorial actors: public administrators, territorial management bodies, producers of goods and services, distributors of goods and distributors of services, users, and workers. The process of adopting integrated models of development and circular management therefore can and must

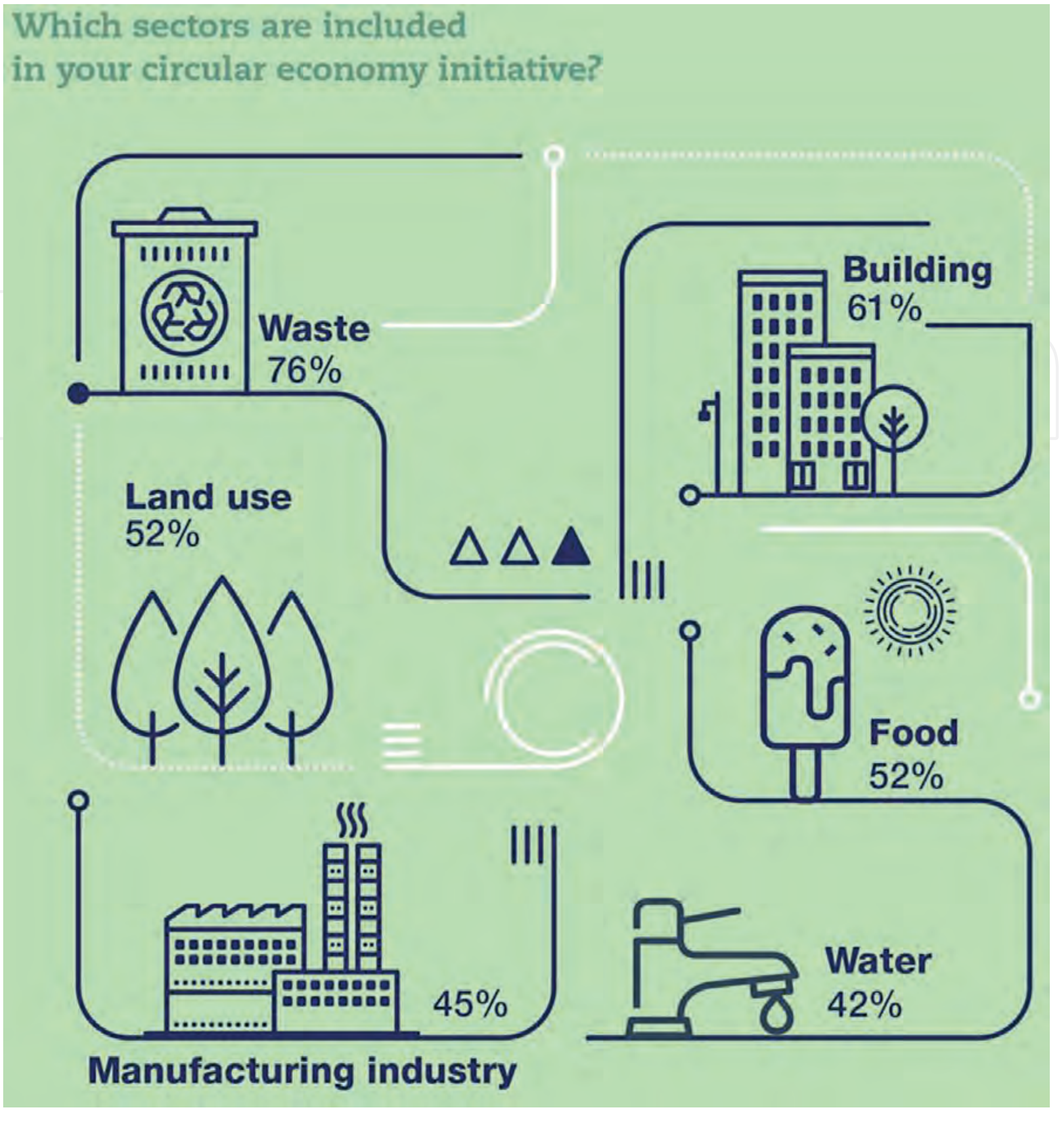

Figure 1.
Fifteen out of 34 cities and regions have a circular economy initiative, where buildings are included in 61% of cases. Source: OECD [9].

be increased and made more effective through coordinated and decisive support by public governance at the level of all sectors of the national production chains, but above all through the organization and the efficient management of the territory as a generator of economy and consumption in a circular sense [8].

Cities and regions are implementing territorial and urban policies oriented toward a multiplicity of experiments with technologies for reduction, reuse, and recycling, but these practices today tend to be sectoral, far from the adoption of integrated management and programming models for functions. Such integration could, in fact, make the various phases of production and management of material and energy flows coherent, by coordinating the activities of the various actors (public administrators, land management bodies, producers of goods and services, distributors of goods and services, users, and workers). The process of adopting integrated models of circular development and management can be increased and made more effective through a coordinated and decisive support of public governance at the level of all sectors of the national production chains, but above all through the efficient organization and management of the territory, as a generator of economy and consumption in a circular sense [8].

What is needed, therefore, is a decisive acceleration in the change of perspective toward circularity: it is necessary to overcome the sectoral, vertical, and fragmented nature that characterizes the circular interventions at the urban scale in the current panorama. Instead, circularity should be considered as central to the eco-systemic and economic functioning of cities and also in their interaction with peripheries, which should be systematically reorganized by putting circularity at the basis of all processes and exchanges of resources that take place at the urban level (food production and consumption, buildings and infrastructure construction, energy production and use, water use and recovery, etc.).

2. The importance of materials reuse in the construction value chain

The key areas for the implementation of an "urban policy for transition" are mainly oriented toward the reuse and recycling of materials from the building processes and urban value chains (urban mining), through the creation of materials management and recovery hubs and the adoption of reuse practices for the existing building stock [8].

At the EU level, the impacts related to construction activities are even higher than those cited at the global level: the building and infrastructure sector uses nearly 50% of the materials in EU by weight; buildings consume 40% of the EU energy and are responsible for 35% of EU GHG emissions [11]. Indeed, the level of material resource efficiency in the European building sector needs to be improved, in order to increase the contribution of the built environment to decarbonization and circularity, tackling climate change and resource scarcity. Through the Roadmap to a Resource Efficient Europe, already in 2016, the EU emphasized the severe impact of the consumption of raw materials in the construction industry, which represents 50% of excavated materials each year. In addition, the total amount of Construction and Demolition (C&D) waste produced annually in the EU represents almost half of total waste, with a recovery rate that is quite high for many member states, but much uncertain for many others. The necessity to significantly boost the closing of production cycles in the building sector was stated by the EU Dir. 98/2008 on Waste, which called for the increase of reuse, recycling, and material recovery of C&D waste to a minimum of 70% by weight by 2020. This target, which has been achieved by many Member States, among which are Germany, Netherlands, and the United Kingdom, for some countries it is particularly ambitious. The Italian situation, apparently in line with the EU threshold for C&D waste recovery (78.1% in 2019, not considering small quantities of C&D waste that do are not counted and the fly tipped waste) [12], is hindered by the lack of complete and reliable data—due to a partial traceability system—on which to develop an efficient C&D waste policy, by planning appropriate strategies and infrastructures.

However, even the virtuous countries must face a new challenge, highlighted by the abovementioned EU Directive, which places reuse above recycling in the waste hierarchy. In fact, in order to close building materials cycles reducing both energy and material consumption, it is necessary to integrate the two strategies, promoting reuse over recycling whenever possible [13]. At present, while high-quality recycling of C&D waste begins to spread, prevention and reuse, notwithstanding their great environmental and energy potential, are still rare. Both reuse and recycling are valid strategies, but their environmental benefits must be considered on a case-by-case basis. While in the future we ought to use only recyclable or biodegradable materials in buildings, so that they can be infinitely regenerated in a closed-loop model [10], as far as existing buildings are concerned, reuse is often the best option in environmental terms [14]. This is particularly true for clay bricks, stone slabs and blocks, steel elements, and other components with high embodied energy and a low performance decay. The Olympic Park in London represents a best practice in this sense [15]. Reuse, despite being well spread in the past, was almost completely abandoned by the construction industry. It only endures in restoration interventions, particularly in countries such as Italy, which often resort to reuse in the preservation of historical buildings. Nevertheless, in the contemporary circular cities' visions, the closed-loop construction value chain—as envisaged, for instance, in the Amsterdam case (**Figure 2**)—a crucial role is played by all the processes that are needed to allow reuse: deconstruction, selective demolition, separation and stocking of reusable components, eventual remanufacturing, repurposing within other construction sites. This model interprets the urban built environment in the perspective of a "reusable city," with buildings meant as "material banks," a concept deeply investigated in the recent H2020 Research Project BAMB (Buildings As Material Banks) [16].

Moreover, in order to favor a sustainable management of building materials and a higher resource efficiency, there are three crucial factors. Firstly, an accurate quantification of the potential supply and demand of secondary materials on an appropriate area (regional/local scale) is needed. This can help in promoting secondary sources of building materials within the urban planning and in forecasting the withdrawal of resources (such as sand, rocks, and aggregates) from the environment. Secondly, a wide range of tools supporting the operators of the building sector can factually help to implement the eco-effective management of waste materials, such as pre-demolition audits or software for the monitoring of waste production on large construction sites. A third factor, which will pay off in a longer term, is the mapping of secondary sources of materials not coming from building sites but rather from the industry, not necessarily from value chains directly linked to the building sector.

The quantification of supply and demand of inert waste and recycled aggregates at the regional level, experimented in a few studies in literature in the last decade

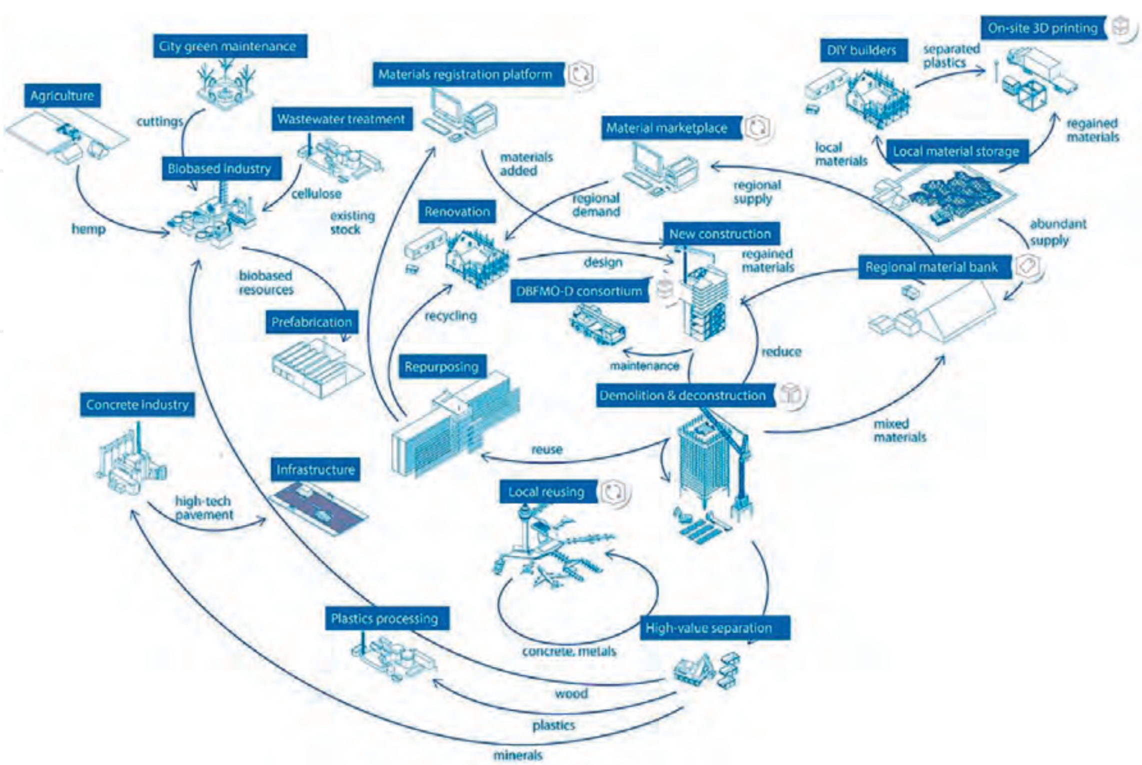

Figure 2.
The vision of a circular construction value chain at the urban/regional scale. Source: Circle Economy, TNO and Fabric [7], redesigned in World Economic Forum [6].

[17, 18], suggested the possibility to investigate, with a similar approach, the *resource conservation potential* deriving from the reuse of building components and waste materials coming from other industry sectors. This research approach will be described in Paragraphs 3 and 4, while the next sections describe in detail the three above mentioned factors through state-of-the-art experiences.

2.1 The estimation of the stock of materials in the existing buildings on an urban scale: Top-down and bottom-up approaches

Quantification, at a neighborhood/urban district scale, of the sources for the potential procurement of secondary building materials is a challenging task, to which European countries are starting to approach, in different ways. A good example is Germany, where different valid methodologies are applied, in order to correctly plan the economic and infrastructural development of the recycling industry. Data can derive from statistical analysis on building stock (top-down approach), such as Material Flow Analysis applied to regional level [17]. Data collection can also be carried out by surveying the materials constituting individual buildings (bottom-up approach) and aggregating the data for homogeneous portions of the building stock [18].

Further research experiences on the topic were illustrated within the SBE19 Brussels BAMB-CIRCPATH International Conference, conclusive of the cited H2020 Project BAMB (Buildings As Material Banks) (2019). The most interesting three are illustrated below.

The REBUILD (REgenerative BUILDings and products for a circular economy) Project, coordinated by Exeter University (UK) [19], addressed the possibility of creating value from the remanufacturing of components from buildings that have reached the end of service life (EoSL), creating new construction products destined to buildings to be realized according to the design for deconstruction approach, allowing in the future the potential new reuse of the same components. A key step in this research, in this sense, is the quantification of the stocks of bricks, steel, and concrete in the existing building stock at the district level, as well as the analysis of the related barriers for recovery and reuse. The project focused in particular on the analysis of bricks, with the development of a new technique for the deconstruction of the masonry with the reclamation of the single integral brick in a mechanized way, complemented by a study of the possible transformations of the element itself and of its use in new building components.

Another research, conducted at the Technical University of Munich [20, 21], has instead developed a dynamic GIS/BIM model to evaluate the stocks of materials in urban areas and the relative flows of materials activated by the construction of residential buildings. The research addressed both the classification of materials stocks (land registry of raw materials incorporated in residential buildings) and the identification of future flows of demolition waste, in order to predict potential sources of secondary raw materials, establish recovery strategies and more suitable control mechanisms. The potential supply of reusable/recyclable materials was therefore compared with the demand, in order to identify the degree of self-sufficiency achievable in a given territorial area, reducing the use of primary raw materials and transport. The developed assessment model was validated by applying it to the Munich-Freiham district, one of the main urban developments in Germany, demonstrating that a self-sufficient supply of steel (from 2036) and recycled aggregates for the production of concrete (from 2031) can be achieved for the construction of residential buildings.

Finally, another interesting research, developed in Belgium by the Hasselt University with the real estate company Essencia [22], experimented the use of existing databases as a tool to explore the potential of the building stock as a bank of materials. The research reports an estimate of the quantities of materials present in the residential building stock in the Flanders region, based on the combination of two existing databases: one relating to the energy performance certificates of buildings, belonging to the Flemish Energy Agency (VEA), with the general characteristics of the buildings, such as volume, type, surface, and information on the envelope of over 1 million assets in the Flemish region; the other one, developed by Essencia Marketing, containing general characteristics, geometric data, and materials on nearly 6000 new residential buildings distributed throughout Belgium. The research examined both databases and defined methods for combining data and for assessing the (future) potential of the existing building stock as a bank of materials.

2.2 Tools for the quantification of waste materials at the building site level

The tools supporting designers and operators (construction and demolition companies) in the estimation, monitoring, and exchange of waste materials in the design and construction phases play a crucial role in optimizing the level of material resource efficiency and circularity in the construction sector.

In the United Kingdom, for example, the share of C&D waste diverted from landfill has significantly grown thanks to, among many regulatory instruments, the mandatory introduction of Site Waste Management Plans in 2008. These Plans, containing an estimate of the waste that will be produced, as well as the accounting of waste actually produced, provide an accurate data collection in real construction/demolition projects, which can effectively integrate statistical surveys. In England, the collection of data is facilitated by the SMARTWaste program by the BRE [23], an online tool supporting operators in the preparation of waste management plans and in the monitoring of waste on site. The SMARTWaste database enables operators to verify and increase their resource efficiency over time, while simultaneously providing valuable information to public authorities for the optimization of this sector. Such instruments could help those countries, such as Italy, still uncertain on the real quantity of C&D produced/recovered.

Another interesting initiative, with a view to the digitalization of the management of building materials' recovery processes—aimed at optimizing their environmental and economic sustainability—was the publication in Italy of the Reference Practice UNI/PdR 75: 2020 "Selective deconstruction—Methodology for selective deconstruction and waste recovery from a circular economy perspective" (February 2020) [24]. This technical pre-standard aims to define a macroprocess for deconstruction that favors the recovery of C&D waste and is oriented toward the compatibility with the digital management of the process itself and of the material-related information. The envisaged process takes into consideration both existing buildings to be refurbished or demolished and new constructions: for the former, through a pre-demolition audit, a database of materials intended for recycling and reuse is built and used during the intervention; for the latter, it is necessary to compile the database of the materials foreseen by the design project. The deconstruction process is divided into three phases: planning, operational, updating the database/final list of the materials used in the building. The aim of this procedure set by the UNI/PdR is to overcome the difficulties of the current construction waste tracking and management system, which in Italy appears to be a barrier for a concrete practicability of circular strategies. Within the UNI working group, the GEOWEB company offered its contribution on the subject of digital support tools for operators, creating a mock-up that collects instruments and functions covering the following phases: survey; modeling of the three-dimensional geometry of the building; design, planning, and execution of the deconstruction intervention.

The SaaS (Software as a Service) platform supports an end-to-end workflow in which all waste management technical and administrative phases are acquired, processed, planned, validated, and certified. Furthermore, the platform integrates an operational network of services (transport, waste treatment, storage, sale of products from secondary materials) offered by local companies, thus providing information and interoperability tools enabling stakeholders to monitor the process on the territory, to enforce policies, to define capacity planning processes, and finally, to promote incentives for the implementation of circular practices.

Another example of a tool to support the actors of the construction process for enhancing the use of secondary materials is the DECORUM platform, developed in Italy by ENEA [25]. The Platform, in support of all the actors of the supply chain in the decision-making phases, aims at ensuring the compliance of construction/renovation works with regulatory and environmental requirements, in particular with the mandatory national Green Public Procurement Minimum Environmental Criteria (GPP MEC) for Buildings (Ministerial Decree 11/10/2017) defining minimum thresholds of recycled content for the different building materials/products. Moreover, the marketplace section of the Platform gives space to the availability and reliability of recycled materials, promoting their wider diffusion in public works contracts.

Finally, the recent French initiative, which saw the development of the Démoclès platform, should also be mentioned: Démoclès is a traceability model for construction waste, whose methodology is being tested in France to be then disseminated abroad. In fact, the feasibility study [26] of the platform established a European benchmark to identify best practices in terms of traceability for—but not only—construction waste, demonstrating that there are two types of possible tracking systems: those similar to certifications and those that physically track streams accompanied by documents and a "third party guarantor." Furthermore, the study identified the building industry's needs in traceability and allowed the definition of specifications for a specific system, revealing that only a physical traceability of streams would be able meet stakeholders' requirements and enabling the construction of the system and of the Démoclès platform.

2.3 Harvest Maps at the urban district and city level

As mentioned, the most innovative research experiences concerning the design of buildings with a low consumption of raw materials today focus on the reuse of materials and components, not necessarily from the building sector, following an urban mining approach. In particular, some research studies have proposed and experimented the mapping of local sources of reclaimed materials, suitable for architecture but coming from other waste streams, before the designing of the building itself [27], those promoting the valorization of residues *through* the design solution. Indeed, reuse provides not just cultural and esthetic benefits, but concrete environmental and economic advantages, whose potential deserves to be thoroughly investigated.

The process set out by Superuse Studios (NL, formerly 2012 Architecten) is a fundamental reference for the circular project, because it involves sourcing all types of waste materials locally and enhancing their potential through a new design and construction process: the demolition of an existing building can represent the first source of materials; then, sources of other types of waste are sought in the proximity of the project area, opening up to the flows of discarded materials at the urban district and the city level. The project experience shows how it is possible to identify different mines of materials, each one characterized by its own dynamics, referring to different types of residues: End of life cycle products/materials (waste), Construction and demolition (waste), Dead stock (new), Production waste (new), Fast-life (short use). All of these potential sources are geo-referenced creating a graphic map with an overview of the residual materials reused/reusable in the project and their original locations. The map is called "Harvest Map" and its use, within the design process, allows many benefits [28].

The scouting process of waste materials [27] suitable for use in architecture (by-products, defective products, dead stock, leftovers processing waste, C&D waste, etc.) and available in the area adjacent to the intervention site, within a limited distance—on average a radius of 25 km—allows the enhancement of local waste by design, with actions of "superuse" rather than simple reuse, where materials acquire a more relevant technical and esthetic value through the design process. Moreover, this process allows to reduce the energy and carbon embodied in the materials used for the intervention, to avoid consumption and emission for the production and transportation of "new" materials, as well as at to activate small-scale circular economy processes. The research experiences described in the next paragraphs investigate the implications of this early mapping of the materials available on the site of the project, both in terms of optimization of resources use and of material characterization of architecture and the potential for transposing this strategy into a highly repeatable technical option [29].

3. Hypothesis and research objectives

The present contribution reports the results of research activities whose aim is to supplement ongoing studies on environmental benefits of recycling in the building sector, by investigating the potential of reuse to increase the overall eco-effectiveness of construction interventions. The hypothesis to be tested is that for a real reduction of primary materials consumption in the building sector, we need to place side by side the use of secondary materials with two other modalities of supply: the reuse of building components resulting from the partial or total deconstruction of buildings, and the reuse of materials from other waste streams not belonging to the construction sector. Therefore, the reported research activities have tried to understand to what extent the reuse of architectural components and waste materials from other industries can help to increase the resource efficiency at the local scale, reducing the consumption of materials, land, and energy. Final aim of the research is to decline the "circular city" in a specific perspective that of the "reusable city," where the built environment represents a resource to be reused in closed loops of material flows. In order to understand to what extent reuse might integrate C&D waste recycling (in particular that of inert waste, representing the main fraction) and to define the potential for resource conservation related to reuse itself, it is necessary to analyze real contexts to understand the actual availability of discarded materials and components suitable for architecture. In this sense, the points at issue are: the frequency of partial and complete demolitions in town; the instruments that a designer or a contractor can adopt to search for reusable materials; the tools that can be used to signal the availability of materials; the possibilities of activating new and different flows. Given the variety of types of materials from other sectors, which might be adopted in construction, it is necessary to focus on stable flows, constant in time and space, which in some cases can be even more regular than those coming from demolition activities, typically not constant in time and not completely predictable. Specific industrial activities might instead represent a constant source of by-products for the building industry.

The specific research goal is to investigate how reuse can contribute, at the scale of an urban district—and then scaled up at the city level—to reduce raw materials consumption, waste production, energy, and emission in the production and transportation of building materials and components. The scale of investigation has been chosen in order to minimize the impacts of the transport of building materials. Therefore, the research studies have focused on case studies of urban regeneration at the district level, testing the potential impacts of reuse on the life cycle first of a single building, then of a small group of buildings, and identifying, in the end, the factors that make it possible to scale up the results to the urban level. The chosen building has undergone a complete technological breakdown in order to understand, within the deep retrofit scenario, which technical elements are more suitable to be renovated with reused materials. Using a life cycle thinking approach, the average length of the service life of various technical elements, the average frequency of replacement of components, and the duration of the service life of the building as a whole have been taken into consideration. Then the materials requirements haven been considered in order to identify potential secondary/reusable materials available at the local level, taking into account the embodied carbon indicator in order to identify the best option in environmental terms, by quantifying the reduction of CO_2 emission due to the avoided extraction, production, and transportation. This is useful also in order to compare multiple scenarios: the use of primary raw materials, of reclaimed components and recycled materials, of only recycled materials. After evaluating the benefits on the single building, it is necessary to assess the possibility of extending reuse to the building stock at the urban scale, in order to maximize its environmental potential.

Final aim of the research is to develop a procedure (and related verification indicators) supporting the design phase. Thus, the scope in the long term is to facilitate the adoption of reuse as a strategic technical option. These objectives require an interdisciplinary and multiscalar approach, combining different scales of investigation (from the city to the building to the component level) and multiple methods, in order to respond to a new and broader approach to resource efficiency in the building sector.

4. Research methodology

The research methodology is divided into three main phases carried out with specific methods. In order to test the hypotheses defined above and to reach the mentioned objectives, it is necessary to start the analysis at the urban level. The adopted model works on the multiscalar dimension of urban districts, with the aim of redefining the environmental, energy, and social performance of existing quartiers to be turned—through urban regeneration—into circular districts, characterized by high resource efficiency and closed-loop flows of material and immaterial resources, in line with the objectives of decarbonization and climate neutrality. In this approach, the renovation interventions aim at a high level of material resource efficiency in the optimization of the environmental performance of the existing settlements, in order to limit the consumption of raw materials, favoring the supply of "zero km" and/or locally sourced building materials and products and at the same time minimizing the volume of C&D waste through circular strategies, thus reducing the level of embodied carbon in the materials used (**Figure 3**). The renovation of existing buildings themselves is a strategic action in order to reduce the need for materials and limit environmental impacts, both in the short and long terms adopting the Design for Deconstruction strategy.

The first phase of assessment of the adopted methodology involves the identification of the building components and materials that make up the building, the estimation of their volume and weight, and the calculation of the carbon

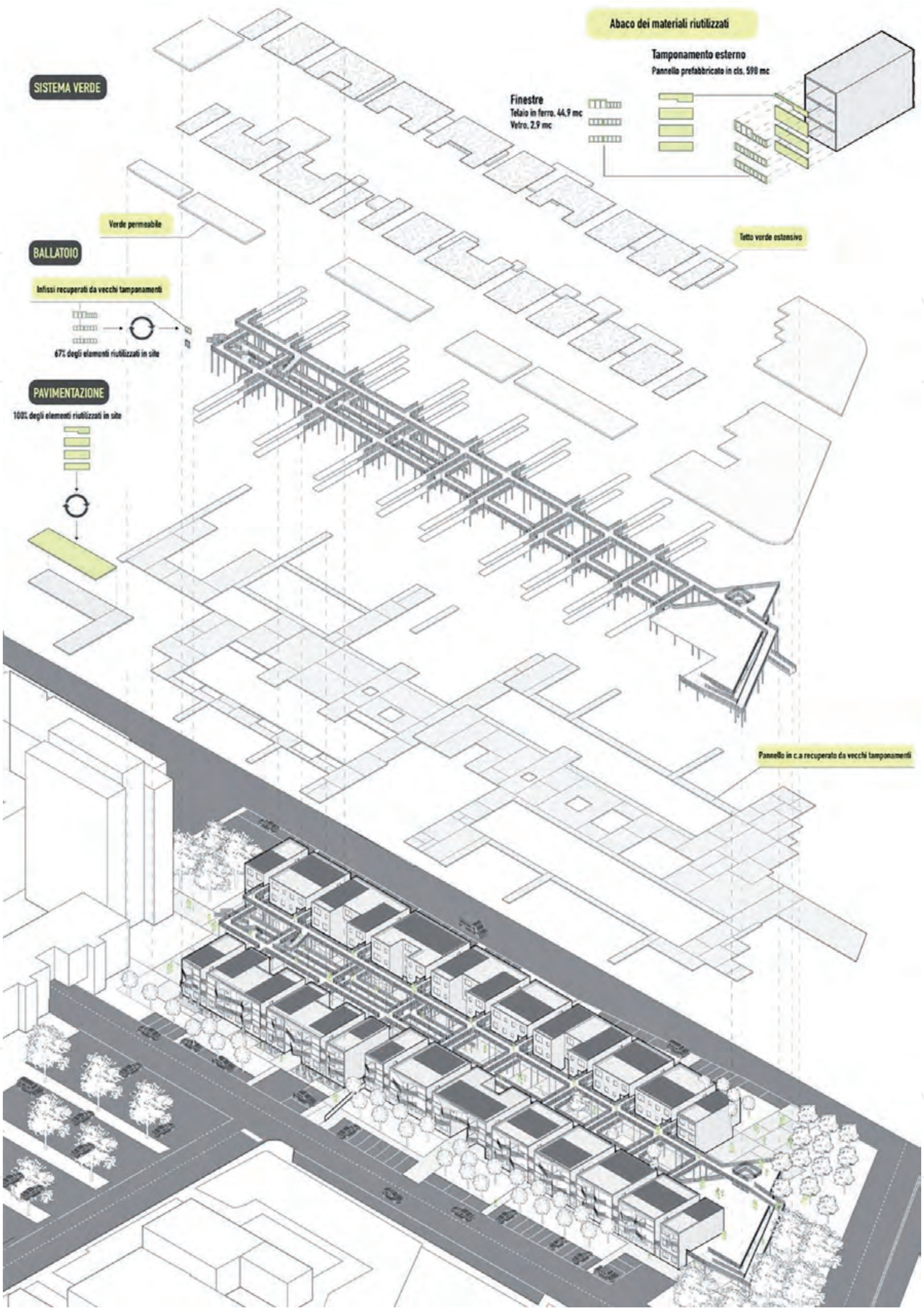

Figure 3.
Circular design process implemented in the design of the linear buildings and the outdoor spaces in the Torrevecchia District, Rome (IT). Source: Research Studies, S. Baiani, P. Altamura with M. Battiata, G. Schiavon, A. Sofi (2021).

embodied in the single materials, starting from a relevant reference database. At the same time as defining the design solutions for the rehabilitation of existing buildings, the volume and weight of the materials destined to be removed from the various technical elements and the relative estimate of the embodied carbon are also quantified.

From a methodological point of view, the evaluation of the level of material resource efficiency achieved is identified through consistent quantitative indicators that allow the measurement of the effectiveness of the choices. In particular, it is possible to measure the recycled content of the materials chosen for the intervention (one of the criteria of the GPP Minimum Environmental Criteria for Construction, compulsory at national level since 2016 for the entire public built heritage); the rate of landfill diversion of materials removed from the existing building; the amount of material recovered on-site; the amount of embodied CO_2 preserved by avoiding the demolition of existing buildings and that preserved through the recovery of materials intended for disposal, in particular on-site reuse or recycling that avoids energy consumption and emission due to transport.

For individual components and materials, potential circular technical options to avoid landfilling are assessed, with reuse as the preferred scenario over recycling and on-site reuse as the optimal solution. The different technical options are compared considering environmental, technological, and economic costs and benefits (**Figure 4**).

The process outlined leads to the integration of three different ways of supplying the materials needed for the deep retrofit intervention: the identification of components that can be recovered from the renovated buildings, during the selective demolition phase (e.g., external and internal fixtures), and that can be subject to remanufacturing and reuse or to recycling and reuse in situ; the identification of sources of waste materials/components/products from buildings or industries in the surrounding area; the selection, to cover the remaining needs, of new renewable and certified materials, which support the objective of reducing environmental impacts and intervention costs, while also ensuring the future reusability and recyclability of materials: "Changing the way products and materials are selected, manufactured and used in the built environment can lower environmental impacts as well as costs. Biological nutrients and sustainable, renewable materials can replace materials that are heavily processed, and hard to reuse and recycle" [30].

It is possible to define the mapping of the sources of waste materials coming from other supply chains (Harvest Map, **Figure 5**), built through an online survey and direct contact with companies, through the provision of questionnaires and inspections aimed at viewing the stocks of materials (surplus, waste, defective products, processing residues, etc.) potentially recoverable in the redevelopment intervention [31].

As part of the experimentation in the urban district of Torrevecchia, in Rome (Italy), online surveys were, as a priority, conducted to identify potential local mines, which were subsequently investigated directly, in collaboration with the respective operators, in order to identify potentially reusable materials. The research led to the definition of a GIS-based map, which identifies potential sources with their inventory of materials, their performance characteristics, and potential uses in relation to the technical elements identified by the project.

The experimentation has identified different typological systems characterizing public housing (ERP) assets (towers and linear buildings) on which the mass flow balance has been developed, considering all the inputs and outputs of materials expected to occur in rehabilitation and maintenance interventions during the whole life cycle.

Through a technological breakdown, with direct surveys and archive research, the technical elements that, on the basis of the project, can be replaced/integrated with recovered components being identified. The evaluation was supported by comparison with projects and experiments that have adopted, with a similar approach, mixed systems containing recovered materials. Through the comparison with case studies, the elements for which the application of reusable components

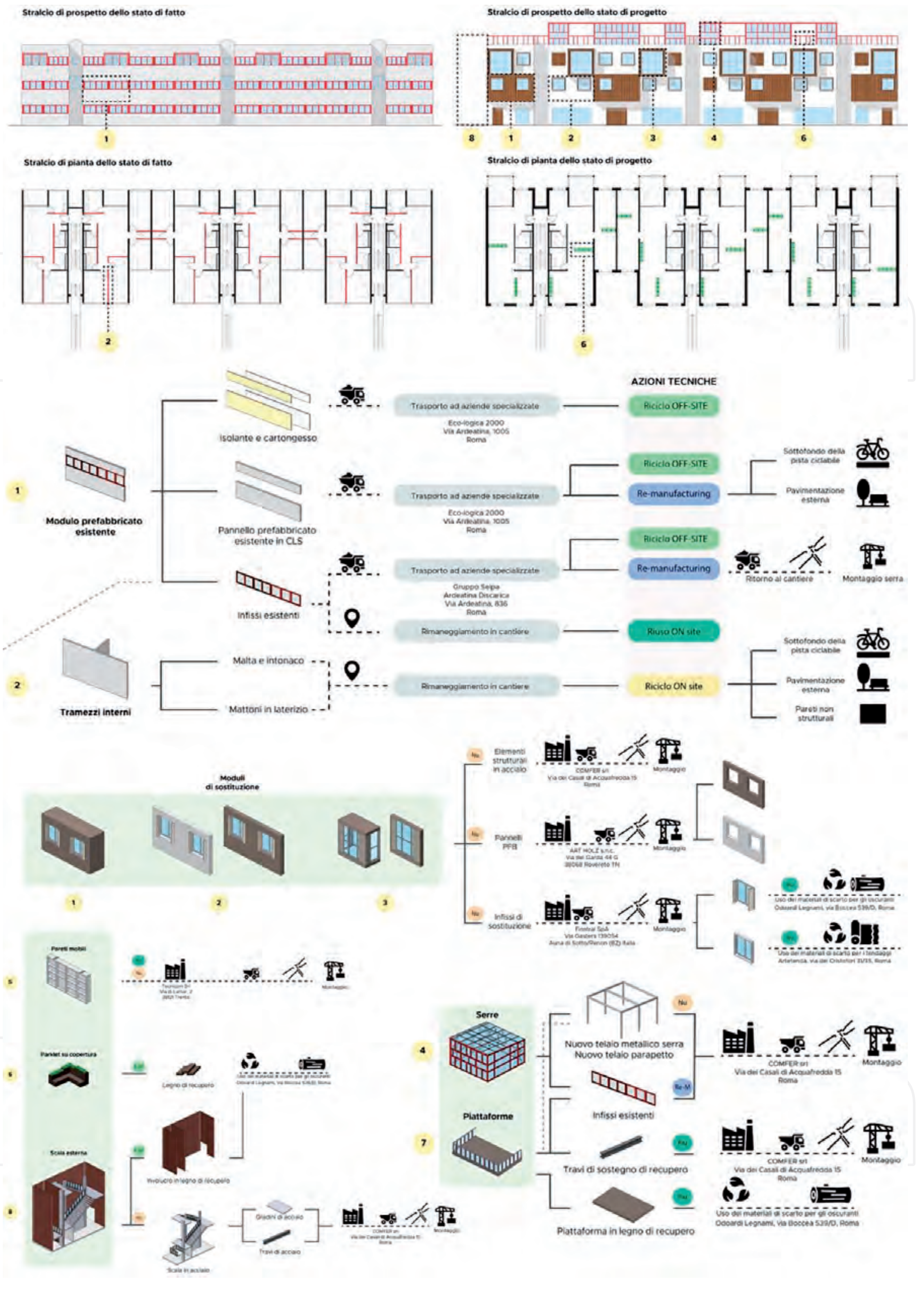

Figure 4.
Torrevecchia District in Rome: Circular building process and its quantitative verification. Research Studies, S. Baiani, P. Altamura, with N.D. Belforte and C. Fabrizio (2021).

is technically, economically, and environmentally more feasible were selected and analyzed in terms of technical requirements and potential performance (**Figure 6**).

An important step in the experimentation is the possible identification of resources on an urban and local scale, starting from demolition materials, reasoning on other types of waste, working on the production of energy at a local level and the reduction of transport emissions, due to the limited size of the district.

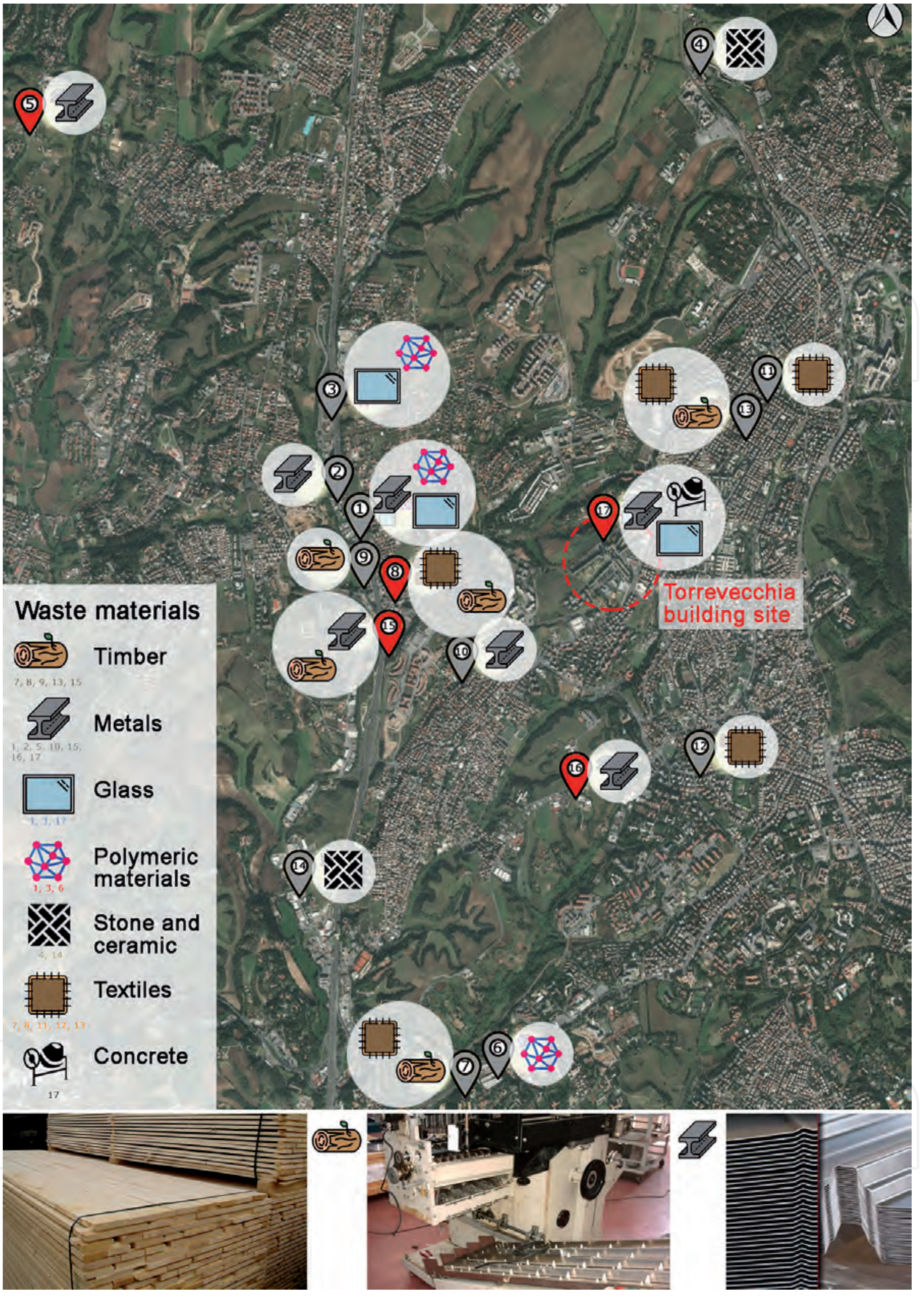

Figure 5.
Harvest Map around the Torrevecchia District, Rome: Map of the companies identified as sources of waste materials around the regeneration site of the Torrevecchia District, within a radius of 6 km. In red, the companies whose waste materials have been chosen for the project. Source: Research Studies, S. Baiani, P. Altamura with M. Rossi and S. Urbinati (2019).

The innovative character of the project lies in the way it verifies the feasibility of reuse in an urban area—and not on an experimental architectural project—to build a dataset that can be used by designers and can be increased by individual users, through shared tools such as the open-source Harvest Map platform. An initial mapping, available to operators in the building industry for the sector, could

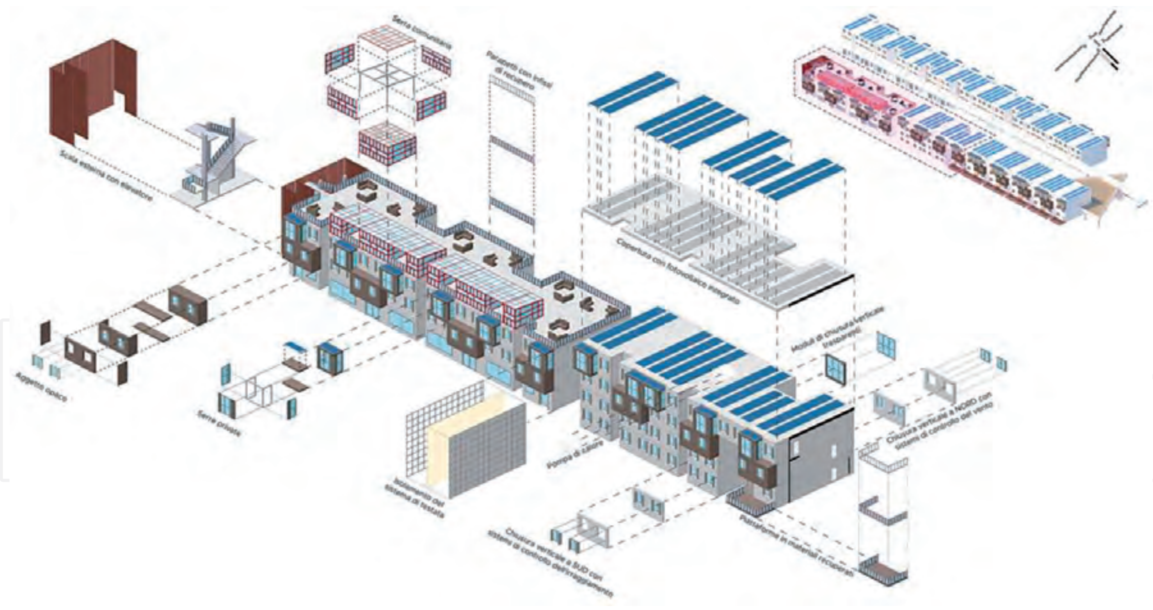

Figure 6.
Technical systems and subsystems of one of the renovated linear buildings in Torrevecchia, Rome: Disassembly of the elements built with reused and recycled materials. Source: Research Studies, S. Baiani, P. Altamura, with N.D. Belforte and C. Fabrizio (2021).

in the future make it possible to direct the methods of intervention, representing a picture—continuously updated—of the material resources available, with significant spin-offs in terms of innovation, involving all the operators in the process.

The experimentation phase, carried out on real cases, examined the potential sources of reusable materials in the city, starting from large construction, demolition, or redevelopment sites. The screening was carried out in an area with a radius of 10–20 km around the project sites, extending the research to more distant areas only in case of specific project characteristics. In the area of the former industrial site Papareschi in Rome (MI.REUSE Project, 2018) [31], for example, the project—aimed at the recovery of the former Miralanza factory with the use of waste materials sourced on site—applied a process that from the scouting phase led to the creation of a Harvest Map, to the redefinition of functions and spaces and the technological design of reversible building components with reused materials [29].

The results achieved in the different contexts, in terms of circular management of building materials in the intervention phase, denote a potentially very high level of circularity achievable through the management of building materials, deriving from partial demolitions and supplied for rehabilitation interventions. Interesting data, derived from experimentation on an public housing urban district in which for each building about 50% of the existing materials are conserved and the remaining half are destined for selective demolition, demonstrate the possibility, through the integrated action of several technical options for the end of life of materials, to reach a recovery quota of materials destined for demolition of about 90% by weight (higher than the 70% threshold of the EU Dir. 98/2008, which GPP MEC have adopted as a criteria) that guarantees to preserve about 80% of the embodied carbon of the materials intended for demolition, which replace new materials for the sub-bases of the external paving, whose environmental impacts are avoided [32].

The investigation involved gathering knowledge about the site in terms of the changes and transformations that led to its current state. Evaluating the building's evolving use has highlighted a series of transformations, which have affected the existing structure at different points in its life cycle. These changes are mainly related to past needs to expand overall living space. A building's life cycle can be analyzed by reading and understanding its construction system. This also makes it possible to understand its peculiarities and limits. In the Torrevecchia District in Rome, in terms of the architectural and construction aspects of the building system, it was made using a heavy and prefabricated system in reinforced concrete (**Figure 7**). This was completed with panels made off-site, limited interior insulating materials and plaster finishes.

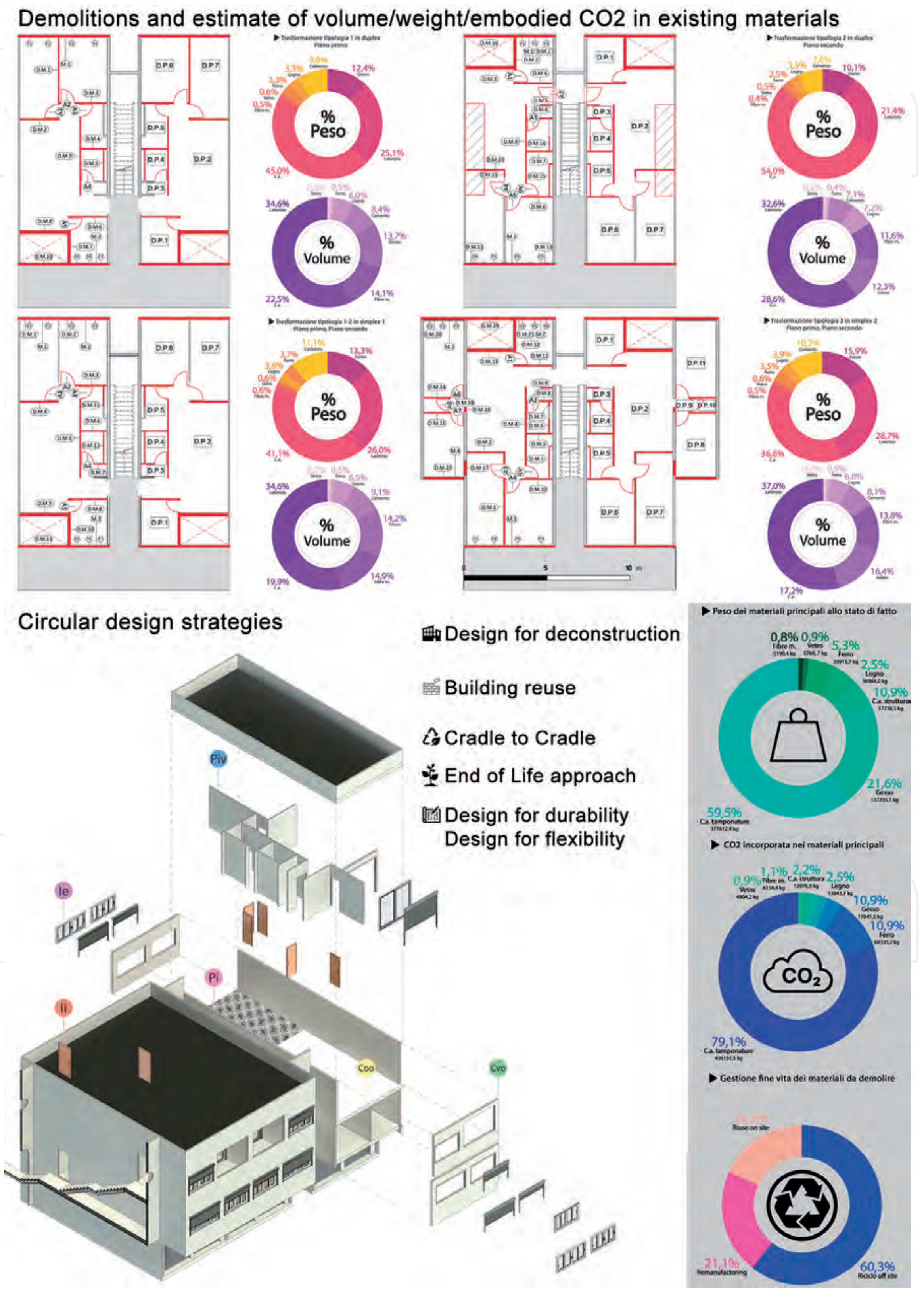

Figure 7.
"Ante operam" state of a renovated building in Torrevecchia, Rome, with the quantification of demolished materials in weight, volume and embodied carbon and the identification of circular design strategies and estimate of the recovery rate. Source: Research Studies, S. Baiani, P. Altamura with F. Ianiri, G. Massaroni, N. Taddei (2020).

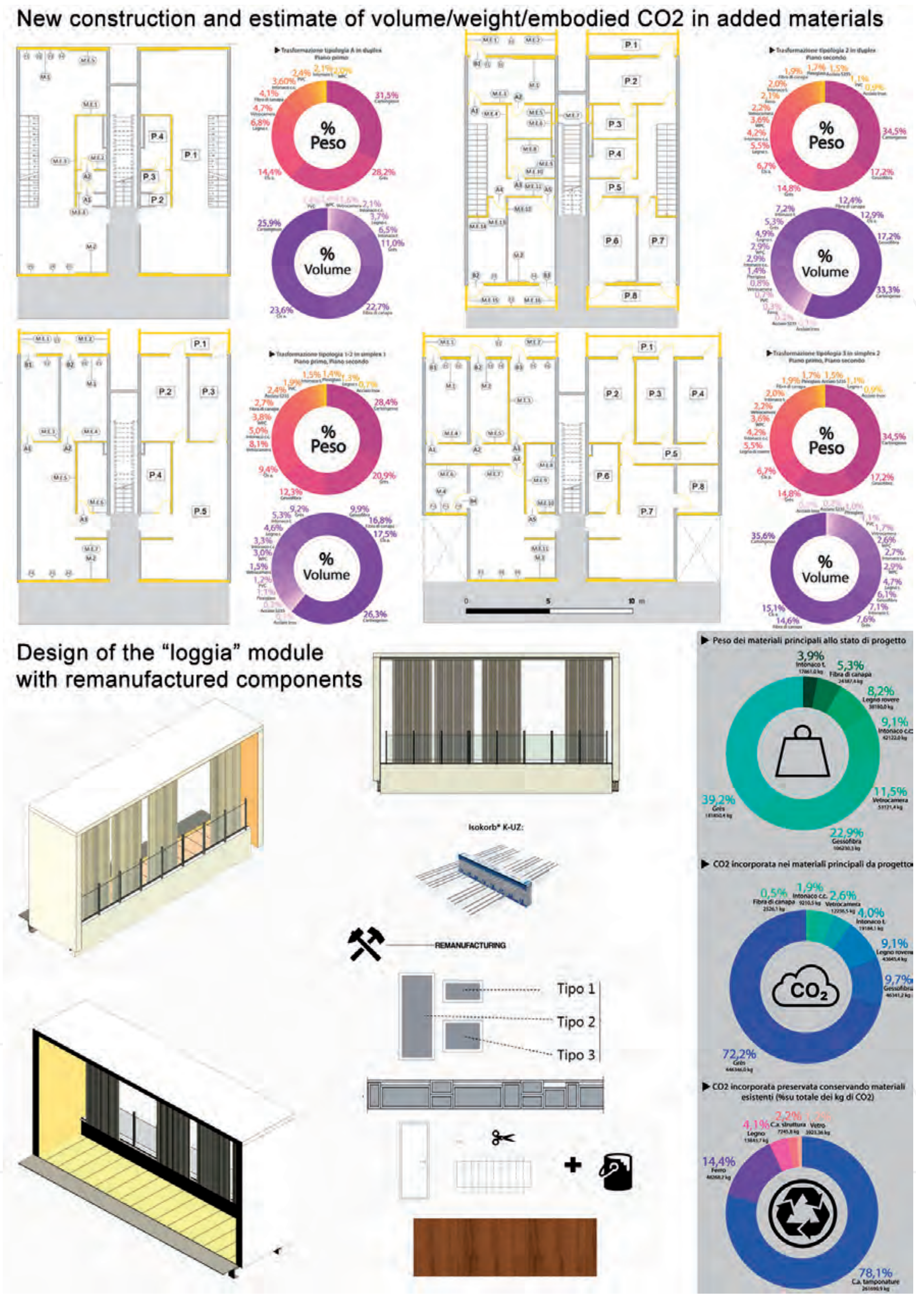

Figure 8.
Design solution for a renovated building in Torrevecchia, Rome, with the quantification of the intervention's materials in weight, volume, and embodied carbon and the calculation of the recovery rate of demolition materials and of the embodied carbon preserved through reuse. Source: Research Studies, S. Baiani, P. Altamura with F. Ianiri, G. Massaroni, N. Taddei (2020).

A comparative assessment was also subsequently conducted to consider the potential effects of resulting demolition waste (in terms of volume/weight). The overall material requirements were also considered under more or less "invasive" intervention scenarios in terms of expanding demolitions/additions. Under these scenarios, various operational choices led to different comparable options based on redefining the housing, introducing/increasing common spaces or living services and identifying components to eliminate or integrate. However, each scenario commonly reflected the guiding technical requirements that interventions be totally reversible, low cost (in terms of environmental, energy, and economic impacts), and material minimizing (in terms of weight and types of materials used).

Estimates were done on materials to be removed from the building in terms of weight and volume, and associated embodied carbon was included in these measurements as well. Estimates were also made in terms of the volume of materials needed to execute each different scenario (these materials were selected based on a set of performance criteria that included maximum decarbonization). This made it possible to come up with a matrix of technical systems, components, and materials, which permitted considering "materials to look for" versus "materials to let go." The Harvest Map was consulted to this end to identify supply "mines." Defining technical systems for each of the options identified (addition, integration, grafting, replacement) has made it also possible to evaluate which existing elements could be recovered and reintroduced over the building life cycle. It also affords systematizing processes of disassembly, micro-demolition, and material or component replacement and recovery. It additionally permits calculating the material/component shares (in terms of percentage by weight and volume), which may come from on or off-site sources. This all made it possible to develop technological solutions while applying a "circular" and "reversible" view of the various elements involved. In doing this, particular attention was paid to the building envelope and the "passive" bioclimatic control devices to be introduced. To this end, verification of energy effectiveness took place as well, alongside with the assessment of the embodied carbon indicator (**Figure 8**).

5. Results discussion and conclusions

By assessing the technical feasibility and environmental potential of adaptive reuse in an urban context, based on the available sources of secondary materials, the experimentation demonstrates the transferability of this strategy in different contexts. This is achieved by proving its significant effectiveness and relevant potential contribution to decarbonization and resources conservation targets. It is possible to identify some specific contributions of the research work, at different levels.

First, the identification of the instrumentation to support the development of a circular design methodology that focuses on the action of recovery and reuse (buildings, components, materials) in order to evaluate how reuse can contribute, at the scale of an urban district—and then scaled up at the city level—to reduce raw materials consumption, waste production, energy, and emission in the production and transportation of building materials and components. In particular, the tools supporting designers and operators (construction and demolition companies) in the estimation, monitoring, and exchange of waste materials in the design and building phases play a crucial role in optimizing the level of material resource efficiency and circularity in the construction sector. Among these: the Site Waste Management Plans (UK) containing an estimate of the waste that will be produced, as well as the accounting of waste actually produced, providing an accurate data collection in real construction/demolition projects, which can effectively integrate statistical surveys; the Reference Practice UNI/PdR 75: 2020 "Selective deconstruction—Methodology for selective deconstruction and waste recovery from a circular economy perspective" (IT) with a view to the digitalization of the management of demolition waste recovery processes, aimed at optimizing their environmental and economic sustainability; the DECORUM platform (IT) supporting the actors of the construction process for enhancing the use of secondary materials; the Démoclès platform (FR), a traceability model for construction waste. Among the tools assessed in the research activities, the Harvest Map was identified as a fundamental reference for the circular project, because it involves sourcing all types of waste materials locally (mines) and enhancing their potential through a new design and construction process.

Second contribution of the research work was the development of a methodological and operational structure, also based on the transfer of international experiences, appropriate to the Italian context, with an experimental approach for the verification of the phases and the evaluation of the results achieved.

Thirdly, through the systematic identification, for each building typology, of elements and technical systems suitable for the realization with reclaimed components, the research validated the compliance of reclaimed elements and materials with specific requirements, with a performance verification procedure.

One potential research perspective opens up, in the definition of an appropriate methodology for the identification and "promotion" of reclaimed components in the urban environment, with a focus on the characterization of virtual and physical spaces (hubs) where materials can be collected and shared with potential users. These local hubs, developed on the basis of the potential demand, which is difficult to correlate with the supply, could constitute an advanced system that could also favor the on-site production of technical components, reducing the considerable impacts caused by transport. The possibility to foresee the potential impact of a greater use of reused materials and components in the building industry favors the reduction of the demand for new materials and opens up new design opportunities in regeneration interventions.

This defines a design vision that focuses on "circularity" in its broadest sense, capable of characterizing the multiple phases of the life cycle of an urban district, through the circular use of materials from regeneration and construction interventions and integrated management of ecological and energy systems, in the broader vision of "reusable cities."

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