Circular & sustainable adaptive reuse of fragile industrial heritage sites. Regenerating Ex SITOCO

RESEARCH AND EXPERIMENTATION

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Abstract. In the fluid design boundaries of technological culture engaging with heritage-urban mine, resilient resource-the research explores innovative experimentation in disused industrial sites in fragile areas. Through environmental design and a lifecycle perspective, it proposes balanced landscape integrations aligned with evolving social, economic, and environmental needs, while addressing multiple risks. The research prioritises control actions on biophysical and morphological components, adopting a circular regeneration approach to reduce the embodied and operational energy of buildings, activating passive functioning to support an "ecologically resilient" transition. The operational, replicable, multi-scale methodology was tested in various pilot cases, exemplified in this paper by the Ex SITOCO site in the Orbetello lagoon.

Keywords: Industrial heritage; Circularity; Material stock; Adaptive reuse; Resilience.

Introduction

Dismissed industrial architectures, memories of a modern archaeology, testimonies having civilisation value, constitute a relevant context supporting the knowledge about materials and construction techniques in the evolution of production systems. Therefore, they need to be framed and valorised in a systemic way, as they contribute to determine the characteristics of contemporary territories. In this view, the absence of policies and strategies aimed at balancing the dichotomous relationship between protection and valorisation produces 'silent remains', empty spaces, places of 'broken windows' (Wilson & Kelling, 1982), reservoirs of materials of anthropic origin, which find meaning in the transition within a broader circular process that connects natural and technical systems (Braungart and McDonough, 2002).

Since the 1980s, many documents by the Council of Europe have highlighted how industrial heritage is a potential resource for society (Pickard, 2017). Within the overarching objective of renovating the EU building stock (European Commission, 2019) and regenerating the built environment to support Europe's climate neutrality targets (European Commission, 2021), heritage, especially when formally listed, might be seen as a challenge for spatial planning (Veldpaus *et al.*, 2020), and calls for more innovative design solutions than the rest of the building stock (Eurocities, 2020).

TICCIH (The International Committee for the Conservation of the Industrial Heritage) states that "industrial heritage is of social value as part of the record of the lives of ordinary men and women, and as such it provides an important sense of identity" (TICCIH, 2003, Art. 2 Par. II). Furthermore, adaptive reuse of industrial heritage can turn it into a catalyst for local development, allowing the reuse and/or recycling of buildings, components and materials, while "keeping those elements that are important to the local community" (Veldpaus *et al.*, 2020). However, from the social point of view, adaptive reuse practices should be participated and balanced to avoid "gentrification processes, commodification, and the exclusion of groups of people" (Veldpaus *et al.*, 2020). Also, to truly make the most of industrial heritage in a sustainable way, an ecological perspective must be introduced into the strategy of its functional reuse (Fusco Girard, 2020), embracing a circular approach. TICCIH underlines how "continuing to adapt and use industrial buildings avoids wasting energy and contributes to sustainable development" (TICCIH, 2003, Art. 5 Par. V). In fact, as stated in the Leeuwarden Declaration (2018), "the re-use of our heritage reduces the consumption of construction materials, saves embodied energy and limits urban sprawl" while at the same time it allows "to undertake a deep energy retrofit, resulting in better-performing, climate-proof, healthier buildings".

In this sense, the Environmental-Technological approach provides a structured, reliable methodology to develop high quality design solutions, ensuring long-term usability, flexibility and adaptiveness of reused heritage to future needs. Adaptive reuse has a two-fold meaning: "re-functionalization, which involves interventions on the building to make it functional again, and conversion, or a change in the function performed" (Della Spina *et al.*, 2023). Therefore, design strategies based on the adaptive reuse approach allow to "change the characteristics of a space based on its changed context", while at the same time "extending the life cycle of buildings with a view to sustainability with minimal interventions of grafting, integration, parasitic architecture, or subtraction" (Della Spina *et al.*, 2023).

Hence, adaptive re-use contributes to the construction of more resilient and sustainable cities and the application of circular economy principles in the built environment (Leeuwarden Declaration, 2018).

Research aims

In the fluid design boundaries of technological culture engaging with heritage – urban mine, resilient resource – the research focuses on innovative experimentation in disused industrial contexts in fragile sites. Through Environmental Design and a life cycle perspective, it defines balanced integrations to the landscape, compatible with changing social, functional, economic-productive and energy-environmental needs, considering multiple risks (climatic, natural, anthropic). The research prioritises control actions on the biophysical and morphological components, adopting a circular regeneration approach, integrated with resilient design strategies aimed at reducing buildings embodied and operational energy, activating passive functioning to support an "ecologically resilient" transition.

In fact, the methodological approach, developed within a research Project funded by Sapienza University, is based on the

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intersection of the actions and tools that Environmental Design adopts in the design of systems at a territorial scale (extended and restricted scope), and in the definition of interventions on the built systems to intervene on the existing. The close interrelation of the two levels makes it possible to outline an articulation of iterative phases that develop the complexities of the interventions, operating at different scales with a lifecycle vision, for the validation of each action. Therefore, the research approach embraces sustainable development goals by trying to "retain the original environment while improving the land use efficiency and surrounding resources and environment through design innovation" (Fu & Hou, 2023).

The relationship between industrial heritage and the biophysical components (soil, water, vegetation) of the context complicates the approach to an inter-scalar design, based on the understanding of the existing and potential material and immaterial resource flows, and generated by interference or integration conditions. Starting from the definition of existing architecture as a non-renewable resource, considering also its embodied materials and emissions, the research aimed at redefining the 'end of life' phase to activate a new virtuous cycle through adaptive reuse actions. The latter were particularly oriented towards ecological effectiveness, resource efficiency, and climate neutrality of the contexts in which the industrial sites arise.

The research thus implements innovative methodologies allowing to assess and underscore the value of the dismissed industrial heritage as an urban mine (Luciano *et al.*, 2023). Moreover, following the Cradle-to-Cradle theory (Braungart and McDonough, 2002), the research interpreted the reuse of dismissed industrial heritage as a way of turning something that proved to be unsuccessful into a beneficial resource for both its context and the local community (Van de Westerlo *et al.* 2010).

The experimentation on dismissed industrial sites in fragile contexts, specifically, made it possible to orient the research methodology towards three priority focuses:

– Safeguard the historical, technological, social and scientific values to identify, preserve and enhance the representative features of the building, which communicate its history and identity in the territorial context.
– Ensure the ecological quality of natural and anthropic assets, aimed at restoring/repairing ecological systems with a view to reversing the land degradation process and preventing risks, taking into account specific vulnerabilities and threat factors for the purpose of systemic risk management.
– Circular use of resources and optimisation of active and passive solutions according to a NetZero approach (Zero Soil-Energy-CO_2-Waste) to minimise waste and the use of resources and, at the same time, maximise efficiency (Baiani *et al.*, 2024a).

Research methodology

The research developed an operational methodology in which the stages of knowledge, assessment, design and validation of the intervention of reactivation of dismissed industrial sites are tackled. Starting from the macro scale of management and valorisation policies and strategies, aimed at the recovery of such sites, the research followed a rationale of replicability of intervention modalities to be developed into specific strategies adapted to the peculiarities of each single industrial heritage site, considering the needs of the local specific stakeholders too.

In the first research Phase, a review of international literature allowed to identify approaches, strategies and methods for the circular and sustainable adaptive reuse of industrial heritage. Then, best practices were collected, analysed and compared. Finally, pilot cases for design experimentation were identified, including dismissed industrial heritage sites in fragile contexts (Baiani *et al.*, 2024a).

The second Phase developed and tested the assessment, design and validation methodology (Fig. 1) structured in ten steps:1) analysis of the historical evolution of the factory, productive architectures and local supply chains; 2) typological and technological study of the architecture and infrastructure on the site; 3) material stock estimation (Luciano *et al.*, 2023) to understand the buildings' environmental value in terms of materials and relative embodied carbon; 4) assessment of the microclimatic, biophysical and morphological conditions of the sites; 5) mapping of the existing and potential resource flows, crossing the site (materials, water, energy, waste); 6) identification and consultation of local stakeholders to verify potential unexpressed needs; 7) definition of the functional programme, focusing on the functional and social mix to maximise sustainability in its three pillars; 8) in-depth study of the morphological-constructive strategic approach, based on the results of the previous steps; 9) design of adaptive reuse scenarios; 10) sustainability and circularity levels assessment with a framework of specific indicators related to material resources, energy, water, waste and CO_2 emissions (Baiani *et al.*, 2024a).

The Research Group (RG) tested its approach to the circular and sustainable adaptive reuse of industrial heritage in a set of different case studies (Baiani *et al.*, 2024a). Among the latter, a sub-group was characterised by a high vulnerability of the context, given by the site's environmental and landscape features, and by the peculiarities of the production processes, particularly by critical pollutants released over time into soil and water, requiring a major remediation phase before the proper adaptive reuse process.

The research methodology was, therefore, specified for sites characterised by a strong context fragility with the integration of three dedicated steps, including ecological evaluation of the

01 | Diagram illustrating the research methodology, the authors

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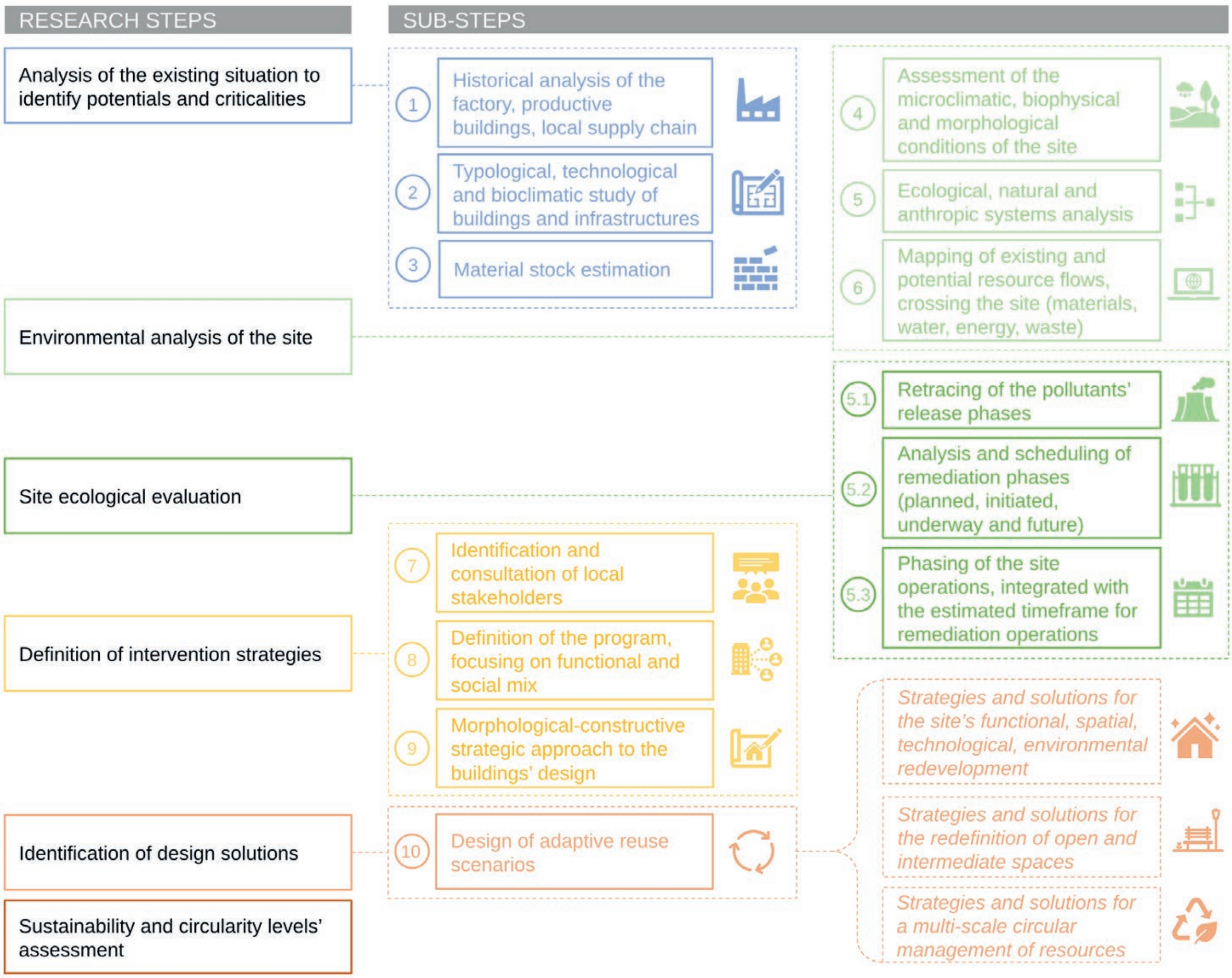

site based on the presence of specific contaminants and pollutants, and then tested and validated in targeted pilot cases. The three integrative steps are: 1) a study aimed at retracing the pollutants' release phases, through the analysis and systematisation of documentary sources, to develop an awareness of the framework of environmental criticalities; 2) an analysis and scheduling of the remediation phases, planned, initiated, underway and future, again based on available documents, through which the estimated timeframe to complete remediation is understood; 3) phasing of the site operations, integrated with the estimated timeframe for remediation operations, to identify opportunities for the progressive reactivation of the site.

The cases selected to test this extended methodology include: the Ex SNIA-factory in Rome (IT) (Baiani *et al.*, 2024a); the Ex SAI in Passignano sul Trasimeno (Perugia, IT) (Baiani *et al.*, 2024b); the waste to energy plants in Colleferro (Rome, IT) (Baiani *et al.*, 2023), and the Ex SITOCO factory in Orbetello (Grosseto, IT), presented as an emblematic case in the next paragraph.

A pilot project for the circular and sustainable adaptive reuse of the fragile site of the Ex SITOCO in Orbetello

The area of the Ex SITOCO, on the Orbetello coastal lagoon, is a very large (over 300 ha) and complex dismissed industrial site, whose characterisation, started by the Italian Ministry of Environment about 30 years ago, revealed a deep degradation of the environmental matrices (heavy metal contamination of the soils, basins, deep waters). The larger context is characterised by important industrial heritage that, since the late 19th century, has taken advantage of the local resources, favoured by the land configuration, with a high landscape value.

Site conditions and background

The analysis of the site allowed to put together the stratigraphy of a complex production system developed from 1907 to 1971. It started with the production of chemical fertilisers by the Società Colla e Concimi which, in the early 1900s, covered 12% of the national perphosphate demand, using pyrite extracted from the deposits on the Island of Giglio and the Colline Metallifere of the Grosseto area. The material was transferred to the site via a navigable canal on the western lagoon of Orbetello. In the 1920s and up until 1958, the Montecatini Company, which had acquired the property (later passed on to Montedison, then to SITOCO and, since 2004, to Laguna Azzurra), consolidated and integrated the factory's layout. Its spatial organisation was based on the production cycle and the railway. The buildings were leaning against each other, converted and abandoned, while maintaining their original rationale and relationships. From the late 1950s, the railway allowed raw materials to be transported within the site via a special siding from which they were conveyed in front of the sulphuric acid building, and accumulated on the forecourt. By means of conveyor belts, the pyrite was lifted to the silos and transported to the furnace mouths, the fumes of which, through an oxidation process, were transformed into sulphuric anhydride and thus into sulphuric acid used for further processing.

The production of sulphuric acid ceased in the 1970s, and the activity continued with the production of fertilisers, which ceased between 1990 and 2006 (Fig. 2).

The Ex SITOCO site is included in the regional 'Piano di Indirizzo Territoriale' (PIT) as one of the historical-cultural values of industrial archaeology for which municipal planning must define the recovery and reuse discipline, safeguarding the façades overlooking the lagoon. The 'Provincial Coordination Territorial Plan' (PTCP) (1999) identifies the Orbetello area as part of the 'City of Water and Stone' subsystem in which it plans to create a 'commercial and tourist system vitalised by highly innovative functions in the recovered industrial areas, among which the multifunctional complex of the SITOCO lagoon, centred on an environmental research centre, stands out nationally'. The area is protected by a landscape constraint (Article 136 of Legislative Decree No. 42/2004) and is included among the Reclamation Sites of National Interest 'S.I.N. ex-SITOCO area' (Article 14, par. p-decies of Law No. 179 of 31 July 2002), due to the heavy contamination of soil and water in and around the site, with an area extended to 200 hectares in 2010.

In fact, the characterisation activities of the environmental matrices (conducted between 1995 and 2003 by ARPAT and ICRAM on behalf of the Italian Ministry of the Environment) highlighted the state of contamination of the soils due to the presence of pyrite ash, rich in heavy metals and arsenic, and the exhausted phosphorite dumps a few metres from the shore, presenting a serious risk of polluting the lagoon basin. Manganese, iron and sulphates were found in the groundwater.

The remediation project and the allocation of the relative funds, since the site is a S.I.N., was taken care of by the Ministry of the Environment, while the remediation works have been initiated and partly already carried out for the public areas by the Orbetello Municipality, and for the private ones by the Laguna Azzurra company, the current owner of the area. The time scenario for the completion of the remediation process is estimated to be around 2030.

Based on the above information, in order to reactivate a new lifecycle for the site, the research defined a broader schedule, from remediation through demolition, conservation and new construction interventions, to the progressive reactivation of the site. The remediation was divided into four phases (Fig. 3, right side): firstly, monitoring of asbestos dispersion in the soil and architectural components, and subsequent removal of asbestos-containing materials and the upper layers of soil; secondly, soil sampling for the presence of other contaminants and removal by excavation, and then backfilling of the area using certified soils; thirdly, the main contaminated aquifer is contained by sheet piling with a trench to drain the contaminated water, then treated and clarified so that it can be given back to the lagoon; fourthly, the settling basins are dredged to collect the deposits, which are screened to separate the materials and sludge; finally, the water is treated for purification. Furthermore, the research investigated alternative and integrative techniques for remediation, based on nature-centred solutions, in terms of potential benefits and costs.

Typological-technological assessment of buildings and material stock estimation

The study of the complex system of buildings was necessary because there are, next to buildings of documentary or cultural value, 'various articulations and parts of no value' (Comune di Orbetello, 2012), which require prioritisation of conservation, and adaptive reuse or demolition operations. The technological-constructive analysis of the existing buildings allowed to map, in detail, the different consistencies of the buildings, their typologies, sizes and constructive systems, as well as components and materials, with the relative levels of alteration and degradation, with particular attention to the residual performance of structural elements. The architecture's typo-morphological articulation, built over a wide period (1909-1970), is characterised by the recurring use of local materials, namely stone blocks, brick textures, concrete portals and timber or steel truss systems. The material stock estimation was developed by mapping the main materials used in the twelve building groups

02 | Typological and functional evolution of the industrial site (1906-1970), the authors with E. Farmeschi and A. Latini, photos from the Montedison Archive

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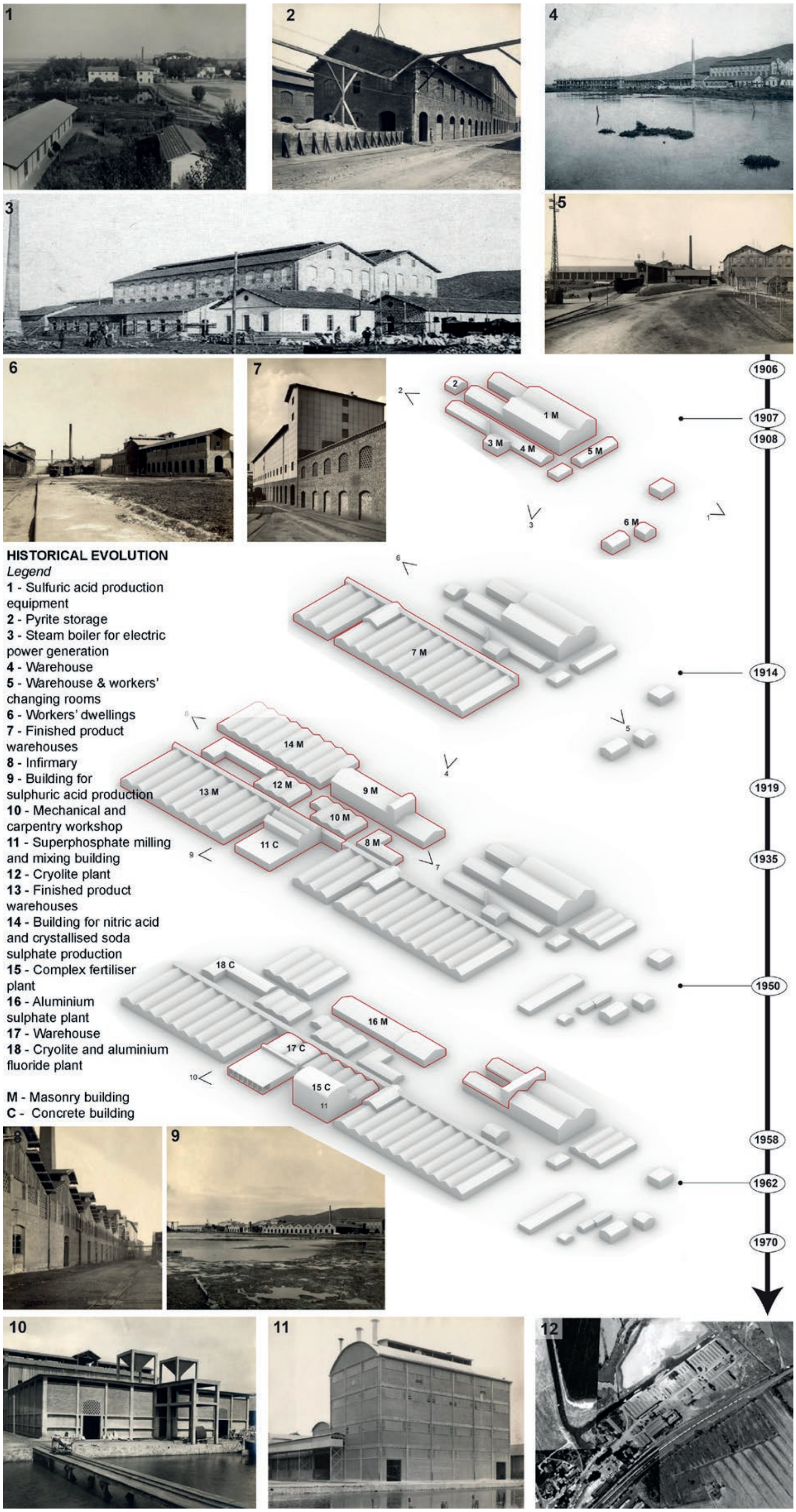

03 | Naturalistic context of the Orbetello lagoon: environmental values and water alteration process, and envisaged process of remediation of the soil, surface and deep aquifer, the authors with E. Farmeschi and A. Latini

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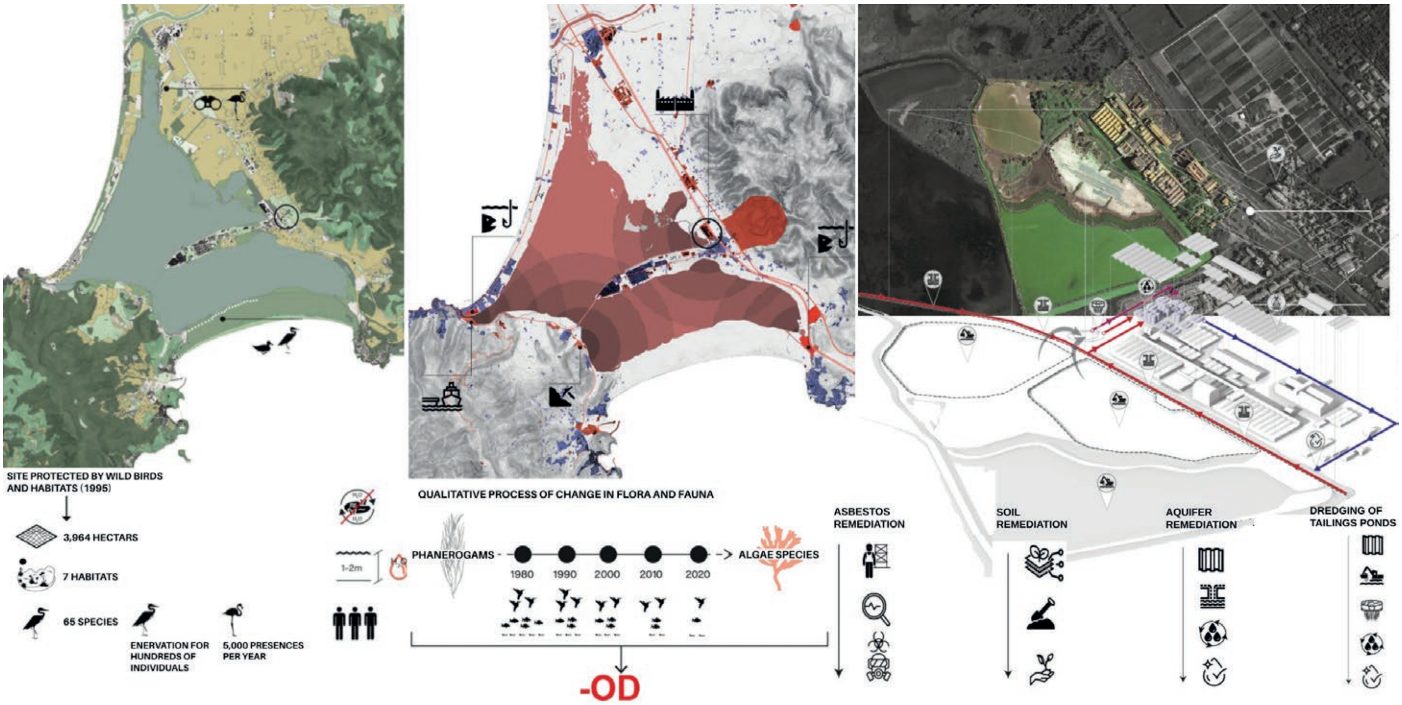

of the site, quantifying their volume, weight and embodied carbon, using benchmark data from the Inventory of Carbon and Energy (ICE) database (Fig. 4). Overall, the material stock is composed of 24,673.340 kg of bricks, concrete, timber and steel, corresponding to around 7,600.000 kg eq-CO_2 of embodied carbon. The main material stock in terms of weight is bricks (56%), while the highest share of carbon emissions is embedded in concrete elements (47%), mainly structural frames, slabs and floors. The results of this analysis proved how preserving the buildings, especially those in bricks and concrete, or reusing their components, means taking advantage of an important mine of materials, while cutting CO_2 emissions in the reuse interventions.

The detailed assessment of the existing stock of components and materials allowed, in the next step, a clear awareness of the quality and residual performance of components, which was essential to assess the buildings' suitability for adaptive reuse – considering their historical/architectural significance, the value of the materials' stock, the spatial adaptability, the level of degradation and, thus, the consistency of the structures. Thus, buildings destined to adaptive reuse, preservation and replacement were identified (Fig. 5), proposing interventions of partial demolition of deteriorated parts that are not historically significant, acting on the original surfaces with micro-stitching, integration and consolidation. Therefore, the preservation of envelopes and structures allows for a coherent and compatible adaptive reuse, reducing soil consumption and emissions in the initial phases of the new lifecycle of the existing buildings to zero, while reactivating the original bioclimatic functioning of the different building types.

Programme definition: a new balance between social and economic goals

The preservation of the existing, collective memory of a production system characterising the local economy, was evaluated through the objective of the site being used by the community for social and collective uses, as expressed in the Dublin Charter (ICOMOS, TICCIH, 2001, p. 5) since 'maintaining the original use or a new compatible use is the most common and usually the most sustainable way of preservation for industrial sites and buildings'.

Based on consultation activities with the Orbetello Municipality, a broad framework of needs was defined on which the functional programme was outlined.

The Structural Plan of the Orbetello Municipality (2007) sees the priority of environmental restoration and securing the site as crucial for the definition of a technological and strategic pole with a high cultural value, also opening up to hypotheses of a didactic centre, linked to the lagoon, and of the creation of accommodation facilities to expand the local tourist offer.

04 | Extract of the typological, technological and construction analysis of productive buildings with the results of the material stock assessment, the authors with E. Farmeschi and A. Latini

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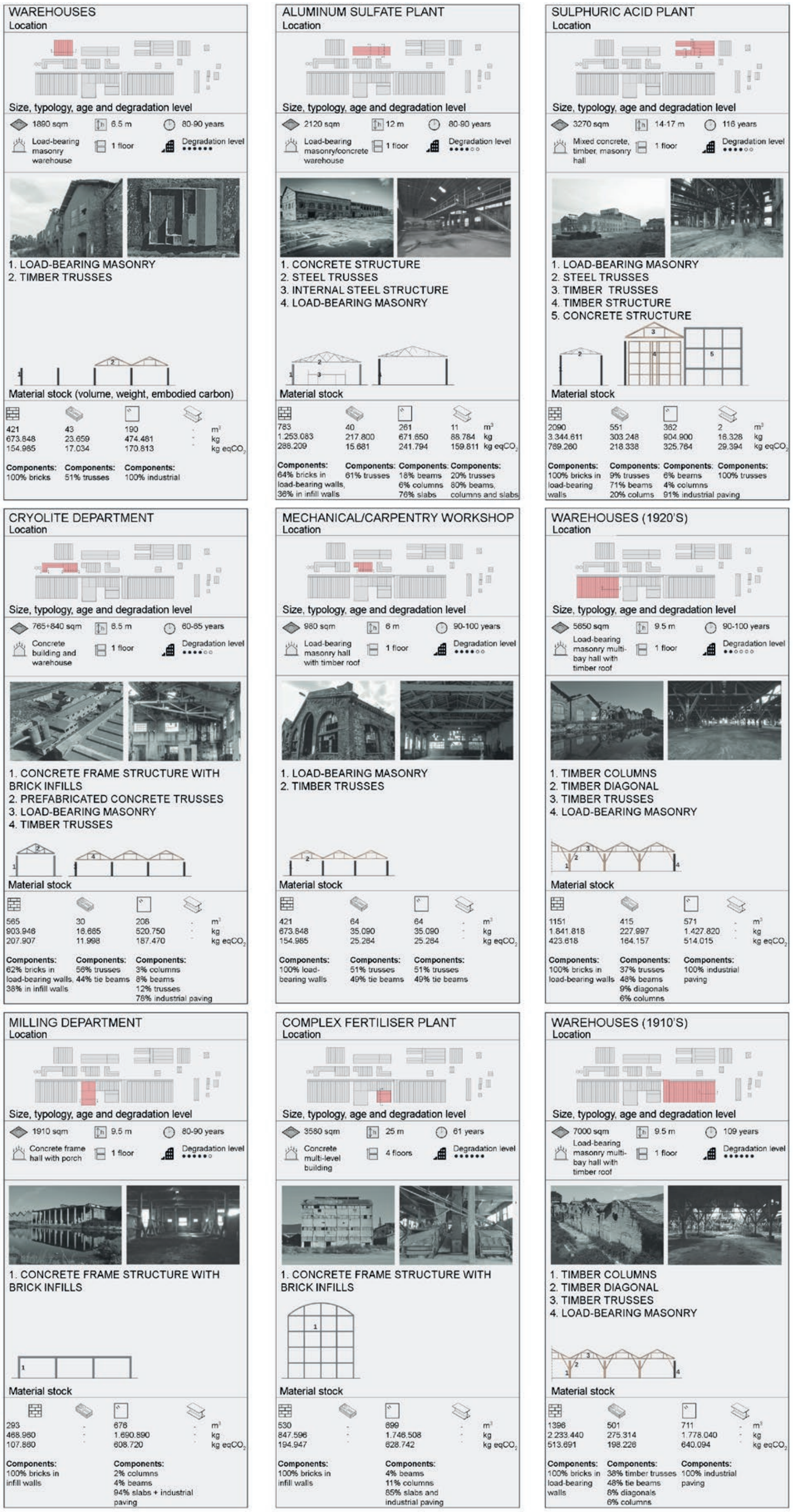

05 | Functional programme, intervention scenarios and design strategies for the whole site and for the single main buildings, the authors with E. Farmeschi and A. Latini

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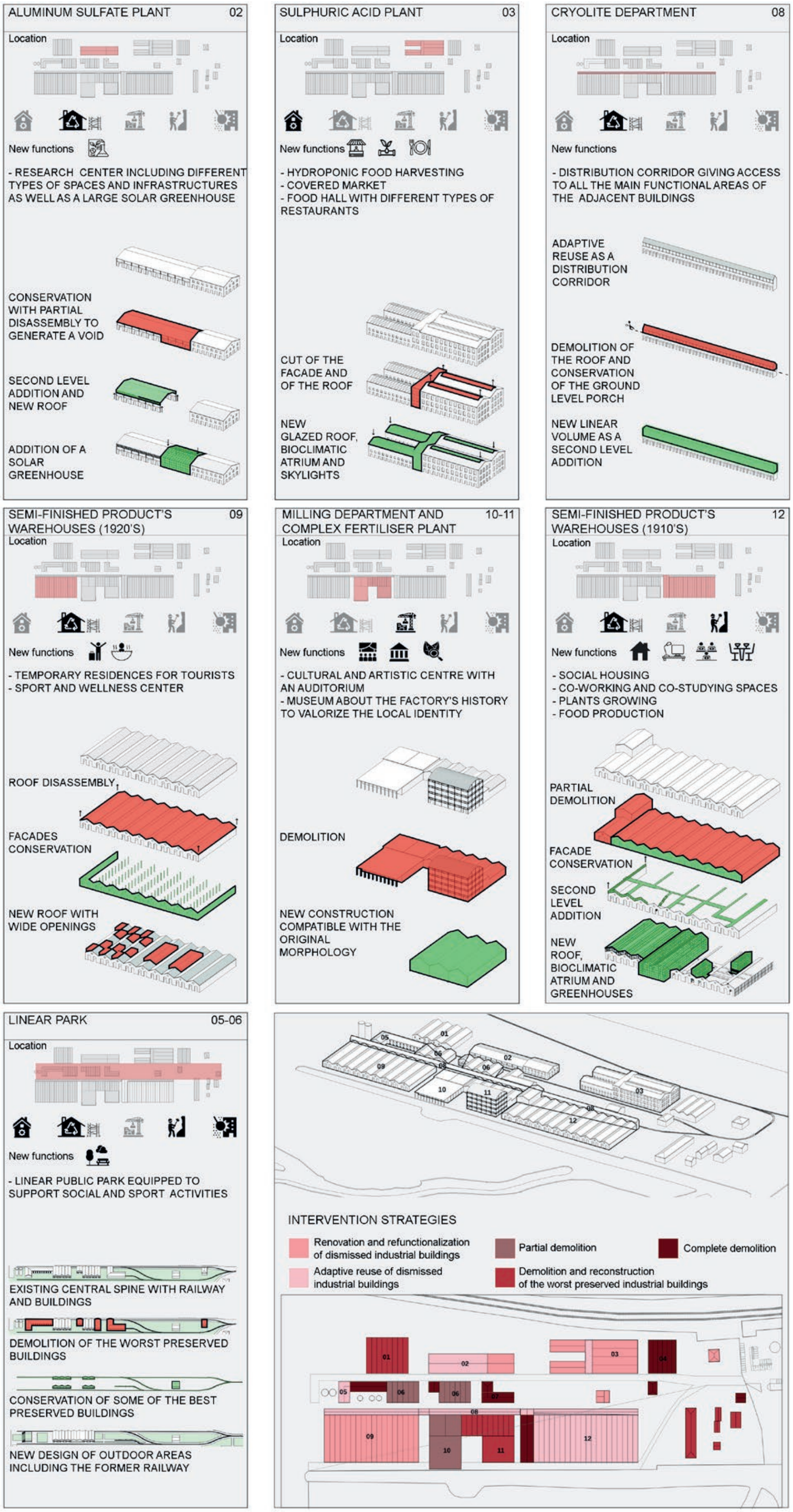

Through the Variant to the Urban Plan (2000), the area is configured as a technological centre, strategic in the context of Orbetello Scalo, with reference to activities and services connected to the water system, intermodality for connections with the islands, environmental didactics, research, tourism, trade and crafts, and management connected to the lagoon (art. 84, Zone D1).
The integration of a very complex planning framework led to the definition of a Functional Programme articulated in 4 main operational areas, compatible with the industrial architectural structure, namely residential, commercial, recreational-cultural and tertiary (services, work, research).
Consistent with these hypothesis, the research has changed perspective for the definition of the intervention programme by moving from profit-oriented scenarios to the privatisation of a large part of the area. This will be achieved through the demolition of most of the existing buildings, defining a scenario that places the public subject at the centre, introducing the central functions of social housing, co-working and the shared production of energy, services and food for self-sufficiency (Guallart, 2014) (Fig. 6). The adaptive reuse scenario defined in the research is thus oriented towards a fully sustainable and circular model, consistent with the landscape, environmental and historic-cultural protection regulations of the area, with a view to the public enhancement of the site.

Circular & sustainable adaptive reuse: reactivating bioclimatic behaviours, adopting reversible construction systems and circular materials

In order to reduce the energy consumption and to cut the operative CO_2 emissions of the reused buildings, the research methodology prioritised reactivation of the bioclimatic behaviour of the different building typologies to underscore the value of passive operation of the built systems, containers of new functions differing from the productive ones, compartmentalised into an overlapping and integrated functional volume (Fig. 7).
The integrated solar and hydroponic greenhouses, inserted in the original brick envelope, ensure an important contribution to the ecological operation of the built system, using recovered rainwater also for the irrigation of vegetable gardens and green areas intruding into the bioclimatic atriums for indoor natural ventilation and cooling.
The remaining necessary energy supply is ensured by the integration of photovoltaic systems integrated into the large opaque and transparent roofs (BIPV), which cover almost 90% of the energy needs.
The intervention methods for the adaptive reuse of the buildings of the eastern and western part of the "Semi-finished product's warehouses" aimed at material demand reduction, reversibility and flexibility, as well as to reducing embodied carbon. The design choices are, therefore, centred on the integration of cross-laminated timber modules, deconstructable, integrable and replaceable, containing shared living, study and work functions, adaptable, flexible and oriented towards overall reversibility. The different structural systems and existing envelopes allow for the compatible accommodation of functional and connective spaces, according to the box-in-the-box model. Thus, through the choice of a timber-based construction system, the reduction of CO_2 emissions over the whole life cycle is guaranteed. The use of additional natural materials (clay, silt and sand), 3D printed, to build functional shells, allows the building systems to be adapted to the different needs of the new functions, guaranteeing low impact, limited physical interference, and high morphological integration of the new elements. The envelopes, insulated internally with rice husk, constitute autonomous passive systems within the larger spaces of the building (Fig. 8).

Discussion and conclusions

The research has developed an integrated intervention model, with an approach articulated in operational phases acting in an iterative manner, to reintegrate a contaminated site into its high value landscape-environmental context and, subsequently, return it to public use, making it central to the life of the local community by reinserting it into social and economic flows.
The first operational level, referring to the remediation of contaminated soil and water, made it possible to highlight and compare some current operations with the hypotheses of exploring different soft and hard methods, with a view to integrating nature-based solutions from the earliest stages of intervention. This approach, to be defined under further conditions of alteration and degradation, could ensure the dissemination of different techniques (naturalistic engineering, hybrid technologies, technical ecological systems) to achieve a 'local' solution that could be part of the wider integrated system of green, blue and grey infrastructures.
The research then allowed to verify site valorisation aspects within the framework of expressed and hypothesised needs, selecting functions compatible with heritage and its memory, capable of giving back areas previously excluded from use to the local community, in line with transformation and regeneration objectives defined based on the consultation with the Orbetello Municipality. This made it possible to define the morpho-technological compatibility criteria for the reuse of disused industrial structures, and to construct a matrix of environmental restoration and adaptive reuse strategies tailored on the context conditions.
The Ex SITOCO area is a particularly complex site, due to the

06 | Functional programme of the eastern "Semi-finished product's warehouses" adaptive reuse: mixed use with social housing, co-working and co-studying areas, food production areas and services, the authors with E. Farmeschi and A. Latini

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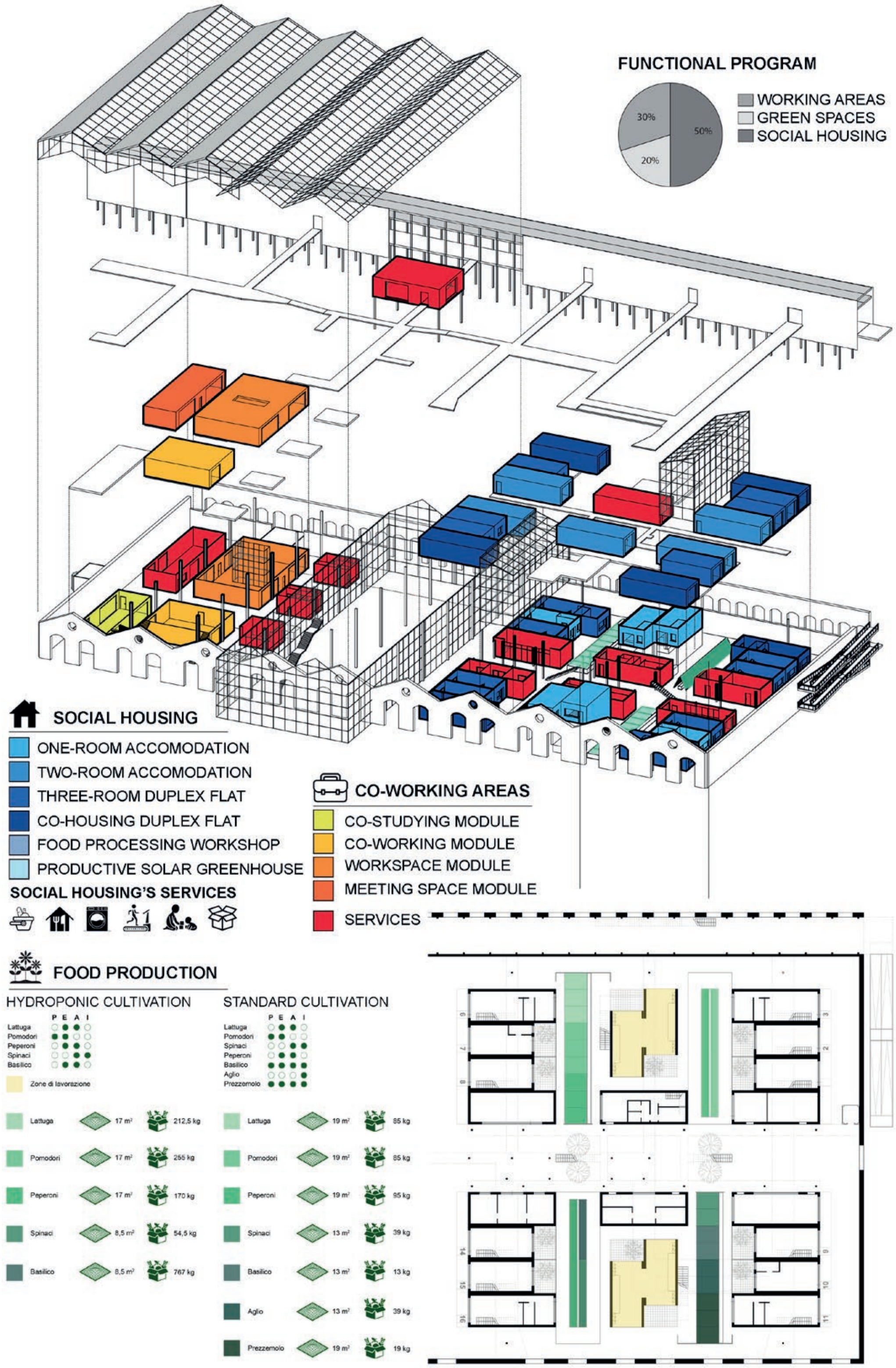

07 | Active, passive and ecological systems adopted in the environmental re-design of the eastern "Semi-finished product's warehouses", the authors with E. Farmeschi and A. Latini

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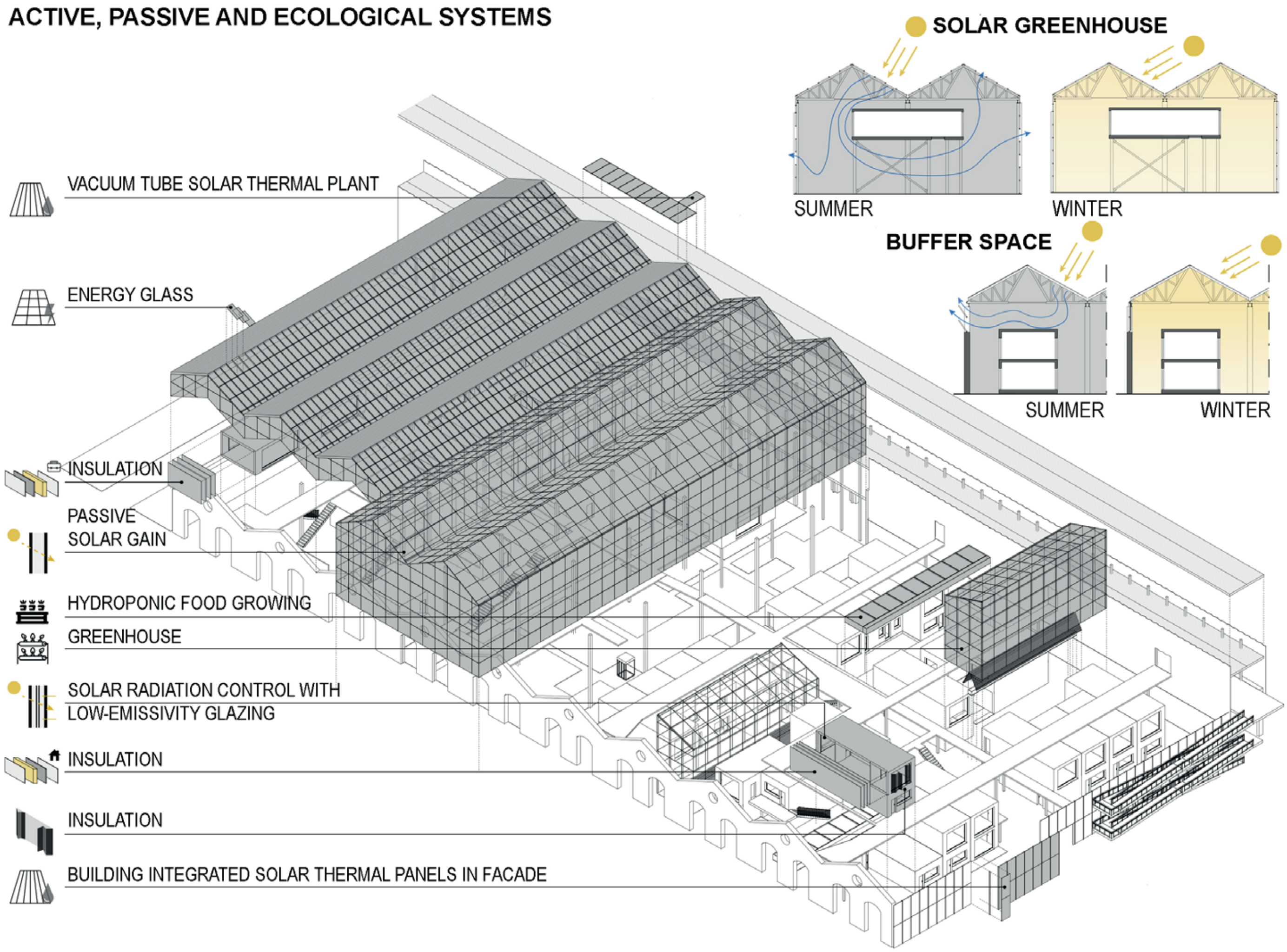
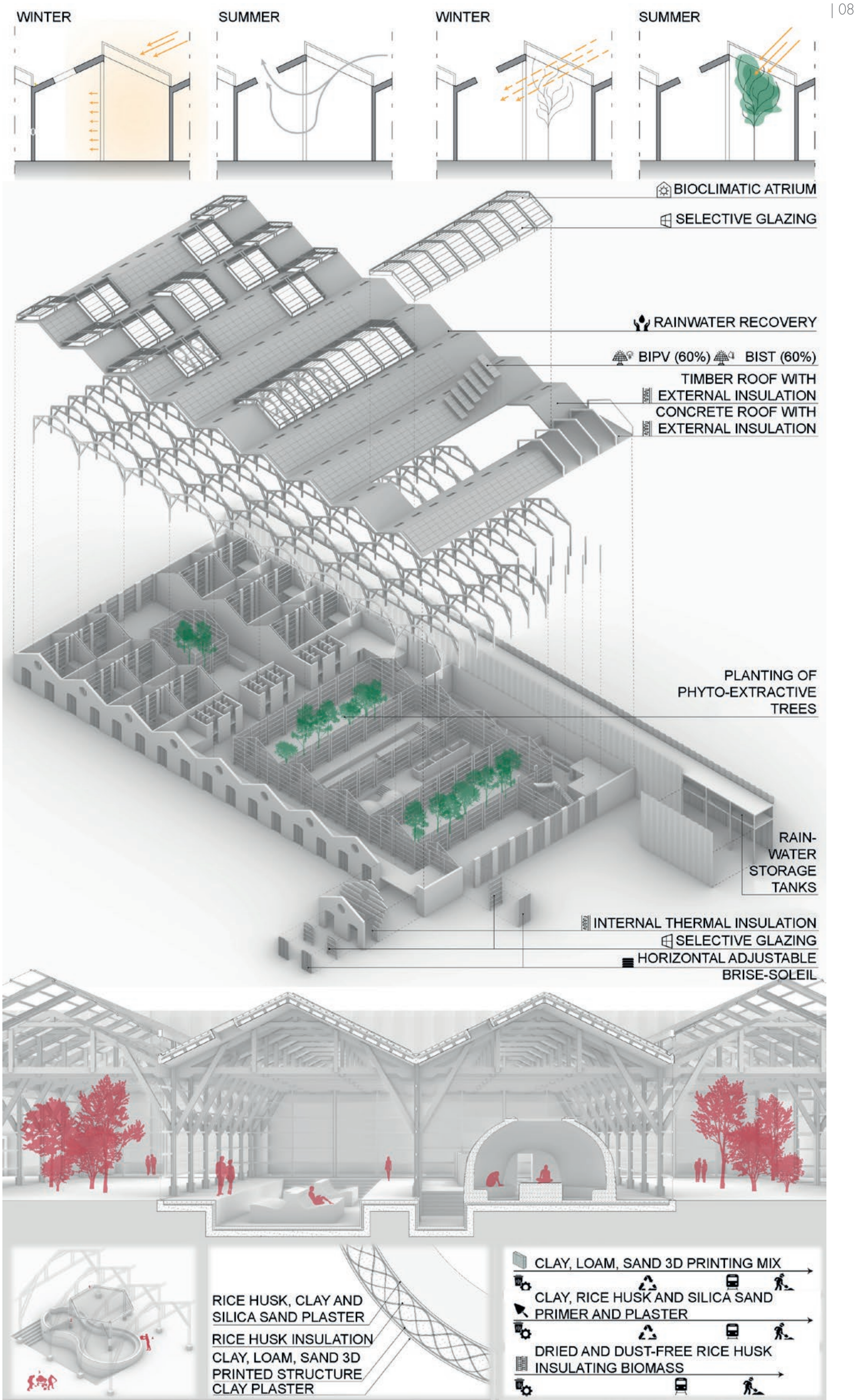


serious and dual pollution of the environmental matrices. However, a broad replicability of the main steps of the methodological process defined in the research is identified, given the extension of the disused industrial sites that, in Italy alone, according to ISTAT estimates, occupy about 3% of the national soil. A fundamental step of the research was drawing a methodological framework, articulated in different strategic levels. Through iterative phases, this allows to identify actions and technical systems for the intervention in fragile contexts, integrating the results obtained in other similar sites and filtering local specificities. The purpose is to define a framework of transferability of actions oriented to support decision-making and operational processes.

One of the limits of the research to be deepened and verified is the difficulty of scheduling adaptive reuse operations, which must consider the long times due to the preliminary, or parallel, stages of remediation, especially when sites are heavily contaminated. Often the critical situation of the sites also limits access for direct site surveys, and the estimation of the stock of materials can only be carried out in desk mode. However, even in such complexity, the assessment methodology implemented by the RG provides a solid foundation for the enhancement of industrial heritage in vulnerable sites by allowing to adopt a holistic approach throughout the design process.

Research perspectives open up in two main directions. Firstly, based on the results of the experimentations developed so far, the RG identifies the possibility of systematising a set of criteria for defining local resource recovery and reuse systems to activate, in the dismissed industrial sites, a proper circular ecosystem with zero-emission energy production. The process will make use of local biowaste to produce materials, ensuring

08 | Active, passive and ecological systems adopted in the environmental re-design of the western "Semi-finished product's warehouses", turned into a tourist and thermal complex, with the use of 3D printing techniques with natural sub-products of rice cultivation, the authors with E. Farmeschi and A. Latini



water recycling and reuse, and integrating nature-based solutions, which could be used as a design support tool/guideline. Secondly, the RG is engaged in developing a methodology for the overall evaluation of the circularity level of the intervention, overcoming the current fragmentation of the existing circularity indicators, referring to individual resource flows.
In the future implementation of such approaches, technicians, policy-makers and stakeholders will be directly responsible for the changes imposed by the process, benefitting from new knowledge and innovations for climate neutral heritage.

ACKNOWLEDGMENTS

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