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REVERSIBLE DESIGN IN THE REUSE OF EXISTING BUILDINGS
Experiments on public housing districts in Rome

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Abstract
European policies are increasingly driving the redevelopment of existing assets within the construction sector. The aim is to boost material and non-material resource efficiency while promoting circularity as well decarbonising. This contribution sees the refurbishment of existing buildings as providing a strategic opportunity to combine design for disassembly and reuse (at the building, system, component and material level) with a 'life cycle' approach. A 'circular' and 'reversible' analytical and design methodology is theoretically defined and verified. This is done by applying this methodology to concrete cases (public housing – ERP – districts in Rome) of funded research and using a set of indicators to quantify the achieved level of effectiveness. This effort reveals original perspectives on how the application of Reversible Building Design to existing buildings can be transferred to the national context.

Keywords
material resource efficiency, design for deconstruction, up-cycling, reversible building design, reuse

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The scope of activity in the construction sector has entirely changed since 2016, shifting from an emphasis on new construction to redeveloping existing assets. The Italian construction market also transformed between 2008 and 2018. Ordinary and extraordinary maintenance carried out on existing structures increased from 56% to 73.6% of all activity (Camera dei Deputati and CRESME, 2019). There has thus been a patent need to integrate examples linked to this kind of transformation with the urgent call to reduce land and resource consumption and use. This, in turn, has affirmed an 'eco-logic' based on the 3 Rs (Reduce-Reuse-Recycle) which is capable of bringing about a new type of virtuous cycle (Life Cycle Redesign). This new logic sees the process of superimposing or creating 'new elements that grow from within (around, below or above)' existing structures as the most sustainable types of design activity.

The built environment offers enormous potential for increasing material and non-material resource efficiency and this is now recognized at the EU level (European Commission, 2014). Life cycle and circularity concepts also support the wider objective of decarbonising and have implications for material resource efficiency. These concepts will be key drivers in building renovation looking towards 2030 and 2050 under the EU Renovation Wave strategy (European Commission, 2020). The goal is to move the construction sector towards an up-cycling approach to the built environment. This, in turn, will reflect the best possible links between resource use, energy efficiency and quality of living.

The international debate | Debate within the current technological culture surrounding this research has focused on 'adaptive reuse' (Wong, 2016), which is viewed as a key strategy for enhancing existing structures. This approach springs from and is based on a multidisciplinary knowledge of the built environment which drives continuous experimentation in terms of grafting, adding and layering. Within contemporary theory and practice, adaptive reuse – also referred to as 'remodeling', 'retrofitting', 'conversion', 'adaptation', 'reworking', 'rehabilitation' or 'restructuring' – means that «[...] the function is the most obvious change, but other alterations may be made to the building itself such as the circulation route, the orientation, the relationships between spaces; additions may be built and other areas may be demolished» (Plevoets and Van Cleempoel, 2011, p. 155). The Plus method, derived from Druot + Lacaton & Vassal's experience in France and applying the Open Building approach, sees a building as potentially flexible, extendable and transformable. This approach is achieved by using dry stratified construction methods and on-demand additive prefabrication. The technical and operational frame of reference is clear. The goal is to ensure functional independence as well as assembly and disassembly (as used in superelevations, add-ons or adaptive, reversible and independent exoskeletons).

From an adaptive perspective, it is therefore possible to outline three levels of intervention with regard to existing structures. Firstly, there is light renovation which involves minimal superficial actions aimed primarily at solving energy-related issues.

Fig. 1 | The Resource Rows housing complex in Ørestad (DK), designed by Lendager Arkitekter (2015-2019), features reused wall facings on the building envelope; these were cut from the walls of an unused industrial building and consist of prefabricated, framed, multilayer panels (credit: Lendager Architekter, 2019).

This can be done by enhancing casing performance (e.g. thermal and acoustic improvement) or with facade restyling. The later may be executed through replacement, substituting obsolete elements (e.g. adding a new skin or re-cladding) and wrapping or encapsulating a surface with a second skin (over-cladding).

A second level of intervention involves various degrees of activity (including medium and deep renovation or high-level renovation as in the Netherlands, e.g. the NPR – National Prjis Renovatie). These kinds of intervention efforts involve extensively transforming buildings and addressing everything from the functional distribution of space to partial micro-demolition, functional unit transformation and distribution schemes (in terms of access, common functions and so on). It may also include increasing building volumes with add ins/ons (e.g. winter gardens, solar greenhouses or enclosed loggias linked to the facade; superelevations linked to coverings; new, contiguous, connected structures linked to the existing building). Thirdly, extreme-level interventions involve extreme make-overs or stripping activity executed via replacement, dismantling or deconstruction.

Such interventions aim to reuse existing building components to the utmost, restore original project functions and maintain any associated micro-climatic behaviours in order to create more efficient living spaces. Efforts have been made along the same lines to reduce the use of raw materials within the construction sector. This has been done by implementing strategies that make it possible to ‘close off’ waste material flows. In fact, construction sector waste accounts for 25% to 30% of all waste generated in the EU, making it essential to step up the use of primary and secondary material sources. At present, only 12% of construction materials come from secondary sources while the building sector overall accounts for 50% of all materials used at the Community level (ECESP, 2020).

Three factors prove critical, therefore, to ensuring material resource efficiency in the construction sector. From an ‘urban mine’ perspective, one issue is the need to accurately quantify the local-level availability of recycled component materials. In this context, materials coming from both construction and other industrial-sector production chains come into play. This information is also essential for planning material procurement within the sector, effectively integrating multiple sources and making the most of secondary sources. With this in mind, the REBUILD Project – REgenerative BUILDings and products for a circular economy (Ajayabi et alii, 2019), coordinated by Exeter University, is a relevant example of recent research in this area. This project set out to quantify the material stocks incorporated into existing buildings in urban areas which could be exploited via circular actions (e.g. reuse of the building or selective demolition aimed at component reuse and material recycling). The design outcomes of such processes have generated solid results in the context of other long-term investigations in this area. Lendager Architekter, for example, have considered producing standardised (potentially industrialisable) facade components with recycled wall facings (Fig. 1). Some researches have alternatively focused on mapping industrial-waste material resources for use in architecture (van Hinte, Peeren and Jongert, 2007). Others have integrated this effort with quantifying available material stocks that could be incorporated into the built environment (Baiani and Altamura, 2019).

Secondly, specific tools aimed at identifying and maximising the potential of selective demolition processes, such as pre-demolition audits, have also proved indispensable and strategically important and are now backed up by specific Guidelines established by the European Commission (2018). Based on the methodologies developed, these kinds of audits can further eco-effective management of waste materials (Altamura, 2015).

Implementing targeted strategies into technological efforts has proved a third critical factor needed to maximise material resource efficiency. Initial analysis in this area was developed in the 1960s by N. J. Habraken. This analysis identified components linked to cities and buildings based on their varying durability levels. This research also affirms Brand's (1994) Shearing Layers of Change principles. In the context of the relationship between main and secondary elements (6S), Brandt identified 'faster strata and slower strata' in terms of degradation. Brand went so far as to argue the need to, «[…] Give people buildings that they can easily adapt to changing requirements or uses with inexpensive materials. For a long lifespan of a building, the change of the 'faster' layers should not be hindered by the 'slower' layers» (Brand, 1994, p. 21).

The Open Building principle has been – and remains – fundamental in defining contemporary Design for approaches. It has proved important because of the need for interscalarity and maintaining an openness to diverse solutions for separating components with varying life cycles. It also remains vital because of the need to define flexible, resilient and collective systems in relation to the Open City, Open Buildings and Open Systems. The broader Designing out Waste (DoW) approach (TRL and WRAP, 2010) was first implemented on a large scale during the building of the London 2012 Olympic Park by the Olympic Delivery Authority (Altamura, 2015). This approach advocates the use of a systematic set of strategies: Design for Reuse and Recovery; Design for Off Site Construction; Design for Materials Optimization; Design for Waste Efficient Procurement; and Design for Deconstruction and Flexibility.

The impact of Design for Deconstruction and Flexibility on technological planning has been so significant that it has recently led to the development of a specific design approach: Reversible Building Design or RBD (Durmisevic, 2018). RBD focuses on reversibility – and therefore flexibility. It allows enhancing existing assets in terms of their space, structure (understood as a system of products) and materials (Fig. 2). In this context, «[…] Buildings designed with three dimensions of transformation open opportunities for a great palette of new value propositions of buildings and its [their] systems, products and materials» (Durmisevic, 2018, p. 1). A fundamental step in defining a reversible building is to identify the various aspects which encourage a transition away from linear structures (that end up in landfills) to circular ones. Firstly, a circular building features spatial flexibility in terms of adaptability (and identifying the minimum core of space needed). Secondly, it reflects structural flexibility (via the technical and functional independence of its components). Thirdly, is has physical flexibility in terms of having different material strata with separable components (which are linked by connections that can be disassembled). RBD is a key driver of the circular economy within the construction sector and this approach highlights the need for design based on the different phases of a building's life cycle. It also encourages reuse scenarios by adopting assembly-disassembly (Design for Disassembly; Guy and Ciarimboli, 2008) solutions for use in relation to building systems, components, replacement materials, updating, integration and deconstruction activity (Durmisevic, 2019).

The goal of the research[1] considered here has been to apply the Reversible Building Design approach to existing buildings, with a special attention to public housing (Edilizia Residenziale Pubblica – ERP) districts in Rome. This clearly involves considering the 'connectors' which comprise the physical links[2] between elements. These have implications for component behaviour and technical issues that emerge over the building life cycle. Moreover, they also help shape innovative architectural spaces and introduce the possibility of creating new types of configurations.

The use of a Design for Deconstruction approach in interventions focusing on existing structures is particularly innovative since it aims for high material resource efficiency. It is also ground breaking in applying Design for Disassembly (either spatially or technically) to create additions, undertake up-cycling (functional, technological, environmental or energy-related) and carry out reversible actions with reused deconstruction-derived materials and components (Melton, 2020).[3]

Interventions on existing structures, like adaptive reuse, can maintain the identity of a building system they are applied to in terms of its values and resources. Such activity may involve approaches guided by distinguishability, reversibility, compatibility and minimum intervention[4]. It may also involve adapting the 'building on the built' principles associated with more restrictive conservation projects. Reversible Building Design consistently highlights that «[…] Disassembly, adaptability and reuse form the nucleus of three dimensions of reversibility and as such determine spatial and structural levels of reversible buildings» (Durmisevic, 2018, p. 2).

Research methodology | The research methodology is based on the life cycle approach as applied to the building system, its components and its materials. This is further integrated with design strategies which enhance material resources while reducing material consumption and waste from a circular perspective. Life Cycle Design ensures an apt intervention approach which considers the whole life cycle perspective. This means adopting 'adaptable reuse' principles in an integrated and interdisciplinary way, thus guaranteeing that the useful life of systems, components and materials endures over time. Interventions involving addition, grafting or integration with an existing structure are therefore in synch with circular processes. Such processes see dura-

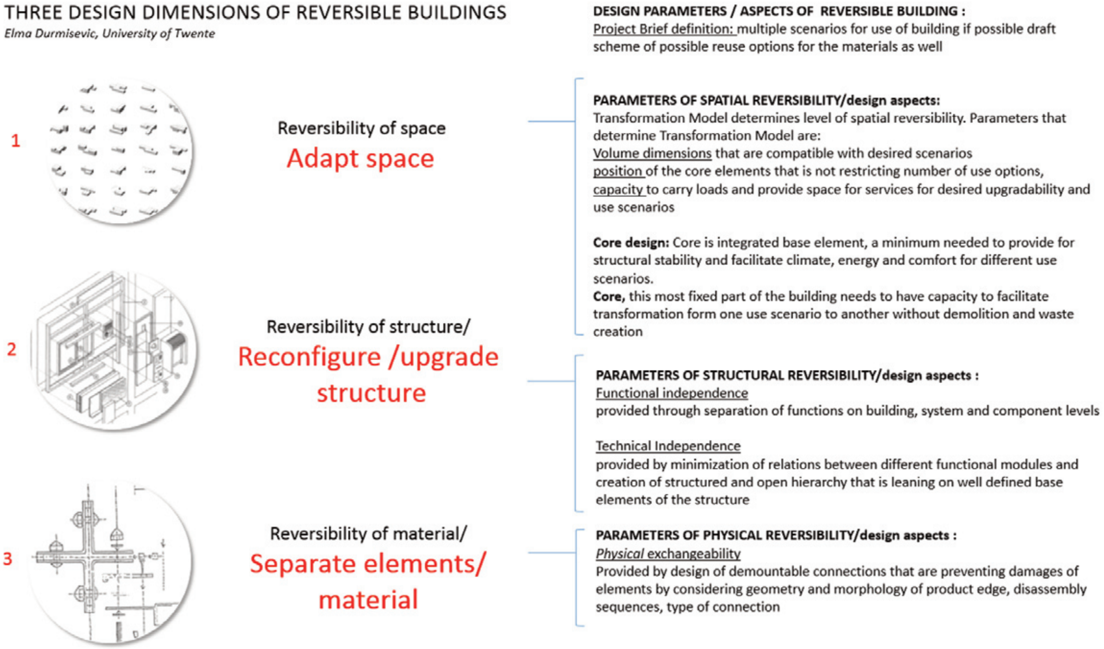

Fig. 2 | The three dimensions of reversibility and their related parameters and requirements (source: Durmisevic, 2018).

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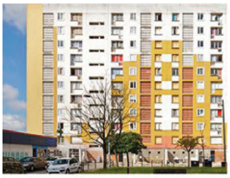
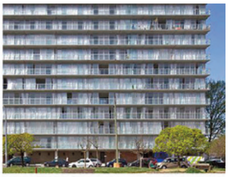
Fig. 3 | The recovery of 530 residential units in the Quartier du Grand Parc, Bordeaux designed by Lacaton & Vassal, Druot and Hutin in 2017 (credit: Lacaton & Vassal).

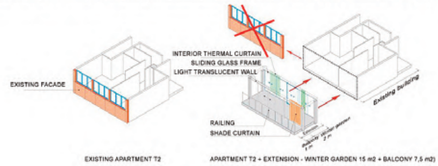
Fig. 4 | The recovery of the Tour Bois le Prêtre, Paris 17°, designed by Druot and Lacaton & Vassal (2011): the project reflects a process/scheme that highlights the envelope's deconstruction phases and the reconstruction of additional spaces (credit: Lacaton & Vassal).

Fig. 5 | The recovery of 709 housing units in the Saint Hilaire Towers, Lormont, designed by Lan Architecture in 2015 (credit: Lan Architecture).

bility[5], adaptability[6], deconstruction[7] and up-cycling as key principles guaranteeing resource efficiency while also contributing to decarbonisation (GBC Italia Circular Economy Working Group, 2020). The actions proposed afford 'juxtaposition' (e.g. of organisms or architectural parts) or 'completion' (i.e. the 'integration' of parts due to missing elements or adjusting and defining a morpho-typological and functional unit). They may also include additions (in terms of a physical and functional extensions) and the 'grafting' of components (which integrate, complete or stratify the existing structure involved). The above activities taken together guarantee durability over time. They also assure the intergenerational transfer of identity and memory which is physically shored up by the built environment.







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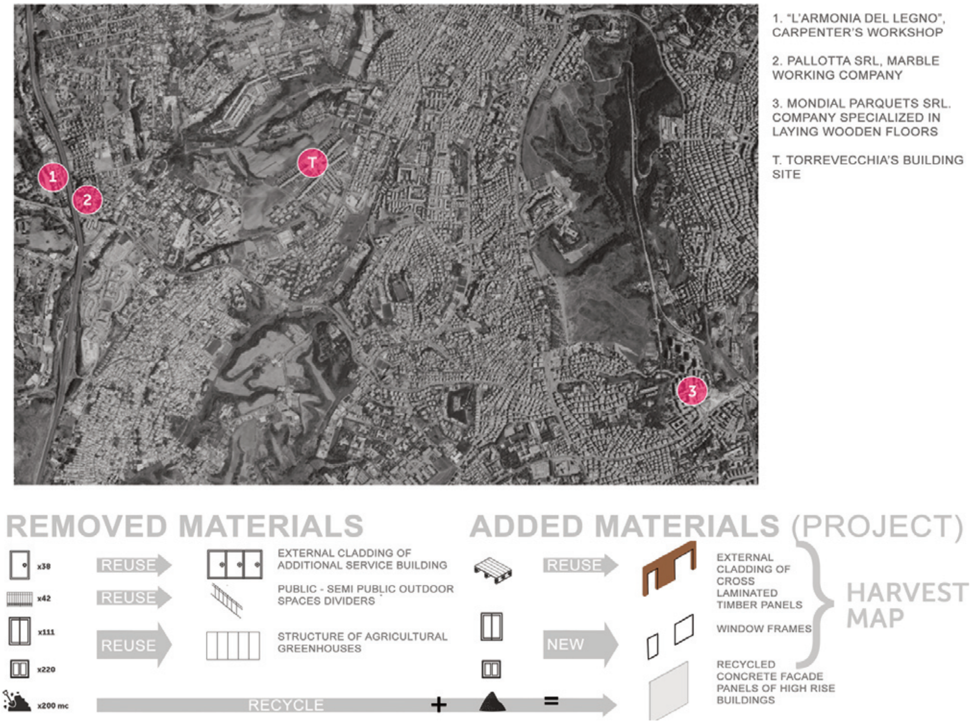


Fig. 6 | The Harvest Map indicating the area around the former IACP site in Torrevecchia (Rome) used to identify 'mines' for materials to integrate into project activity; the map also provides a comprehensive framework of the materials to be added or removed from the building in developing technical solutions (credit: S. Baiani, P. Altamura, E. Fauda Pichet, S. Lucci and R. Menaguale, 2020).

A specific objective of this research is to integrate basic circular strategies in component reuse and recycling with design strategies for disassembly that allow continual recovery over the building life cycle. These basic strategies ensure that the objectives of cost containment and reducing short-term environmental impacts are both met. To this end, «Using salvaged building materials in place of new materials can be an effective means of conserving natural resources, and reducing embodied energy, a well as having tangible economic benefits» (Kernan, 2002, p. 6). The durability of such strategies is achieved through a Design for Deconstruction (DfD) approach which ensures that both recycled and new materials can be recovered while minimising waste production and damage over time. DfD makes it possible to guarantee the reversibility of an intervention on different levels based on specific requirements[8] (Altamura, 2015). This ensures that the spatial set-up of a building can be reconfigured without demolition and that the systems used (including the operating ones) are accessible, replaceable and integrable. It also ensures that the functional strata with their different components are easily separable via fixing and connection systems that have a wide degree of dimensional flexibility.

The technological solutions adopted thus allow for the potential future recovery of components and materials for reuse and recycling at every phase of the building life cycle (over the short, medium and long term). This potential can be fostered by preparing maintenance or graphic communicative plans in the form of 'as built' drawings, which highlight disassembly methods. On the basis of the aforementioned approach, the methodological phases which may be adopted can be outlined as follows:
– Analysis of the existing building's life cycle, highlighting transformations from its origin to current state (this is done by evaluating how building use has evolved);
– Constructive analysis of the existing building and characterisation of its overall system. This includes decomposition to identify the subsystems and components suitable for recovery or recycling;
– Quantification of the materials present in the existing building (in terms of volume and weight);
– Estimating the embodied CO_2 in the existing materials using relevant databases[9];
– Outlining alternative intervention scenarios for redefining the accommodations, introducing/increasing common spaces and supplementary services and identifying planned demolitions and new construction activity;
– Estimating the weight and volume of materials to be removed from the existing building, the volume of material required for an intervention and the volume of the related embodied CO_2;
– Creating a Harvest Map with a maximum radius of 25 km around the intervention site that lists and identifies sources for materials. Mapping of identified waste materials (in terms of dimensional parameters, quantities, production frequency, cost and so on); this information should be drawn up by researching local companies (in desk mode), subsequently contacting them via questionnaires and carrying out inspections in-person to see waste materials (Altamura and Baiani, 2019);
– Selecting potentially recoverable materials for the intervention drawn from demolitions or identified on the Harvest Map;
– Identifying the technical structures that will house on-site recovered materials or those identified through the Harvest Map;
– Defining processes related to planned demolitions, replacement and material recovery from the existing building;
– Calculating the shares (percentages by weight and volume) of on-site reused/recycled materials and components versus those coming from off-site;
– Defining the technological solutions to be adopted for the various elements needed with a view to deconstructability; this means focusing, in particular, on the building envelope which may need retrofitting; the 'passive' bioclimatic control devices introduced are also of interest and should be checked for energy effectiveness.

Measuring the intervention effectiveness levels may be carried out using the following quantitative indicators of circularity: 1) the share of demolition materials recovered by weight, broken down by the circular technical option applied to them (and

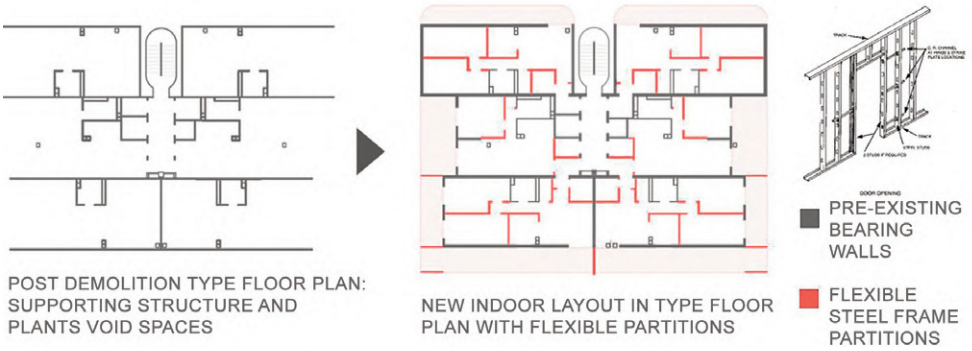


Fig. 7 | The flexible adaptive design of the 'Torri del quartiere di Torrevecchia' (Rome) is achieved by cutting select panels and inserting reversible metal systems; it allows for a demolition-free way of extending housing surfaces (credit: S. Baiani, P. Altamura, N. Bonomi, E. Gianvenuti and A. Ruggiero, 2020).

considered in order of preference relative to environmental impacts: on-site reuse, off-site reuse, on-site recycling, off-site recycling); 2) the overall and specific recycled content used in relation to each project material used; 3) the share of disassembled materials and components used by weight as a proportion of all project materials (excluding operating systems); 4) the distance travelled to procure the materials used; 5) the embodied CO_2 maintained by conserving existing building materials; 6) the reduction in embodied CO_2 achieved by using on-site components or recycled and recovered materials procured off-site compared to a reference intervention made with new materials and standard products. On the one hand, the above indicators measure savings in terms of raw materials and waste production. On the other, they also measure environmental impacts in terms of reduced climate emissions due to component and material level recovery processes and reduced transportation.

The methodological approach employed in this research is partly aligned with the mandatory on-off criteria introduced at the national level in Italy by the Italian Ministerial Decree on Minimum Environmental Criteria for Green Public Procurement for Interventions on Public Buildings (Ministerial Decree 11/10/2017). This decree provides specific thresholds for indicators 1 to 4 above by setting standards (measured in terms of weight). These include the goal of 70% recovery of demolition materials, 15% recovery of recycled materials and 50% recovery of components that can be disassembled at the end of their useful life. The use of extracted, collected, recovered or processed materials coming from within 150 km of the construction site must also account for at least 60% of the total materials used. In focusing on these indicators, the research aims to show the potential for significantly increasing the aforementioned thresholds by using specific design solutions and innovative processes. The methodology considered here also employs measures of embodied CO_2 (indicators 5 and 6) in order to highlight the contribution that the suggested planning and processes can make toward decarbonisation. Furthermore, the methodology is aligned with the common European Framework Level(s) and the associated system of metrics for assessing building environmental sustainability. This framework also promotes a life cycle and circularity perspective, particularly in terms of its macro-level objective linked to Efficient Resources and Circular Material Life Cycles and the related indicators.

Implementation of the methodology in design investigations on former IACP public housing in Torrevecchia, Rome | The Design for Deconstruction methodological approach adopts design and construction strategies aimed at achieving high levels of material resource efficiency. This approach has been applied and verified in different locations in Rome which reflect diverse materials and construction systems dating from different historical periods. Research has specifically focused on a series of public housing (of the former Istituto Autonomo Case Popolari – IACP) high rises in Torrevecchia, Rome. This setting has presented a number of constraints, including a restricted ability to transform building materials and adaptively reuse them in ways that can meet local demands. This is because the cast concrete slabs and tables comprising the building, which were originally made on-site, are very limiting in the face of modern requirements.

The first phase of 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 analysed by reading and understanding its construction system. This also makes it possible to understand its peculiarities and limits. In terms of the architectural and construction aspects of the building under consideration, it was made using a heavy and prefabricated system in reinforced concrete. This was completed with panels made off-site, limited interior insulating materials and plaster finishes.

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 minimising (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 measure-

ments 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 decarbonisation). 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' (Fig. 6). 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 systematising 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. Various alternative intervention scenarios were developed based on combining the identification of materials available in-situ with the different design solutions. These different scenarios included:
– Redistributing internal spaces with an eye for greater flexibility, while maintaining the existing shafts; this would also involve rethinking the internal articulation of space by replacing brick partitions with reversible metal systems; this scenario guarantees flexibility and adaptability while expanding housing surfaces without any demolition (Fig. 7);
– Increasing the number and size of existing openings by the selective removal of the building's precast, pre-existing, concrete panels and inserting shade systems made of recycled materials, thereby ensuring interior comfort;
– Adding external spaces to the housing by inserting external overhangs using X-LAM panels and light-weight, self-supporting structures; these would be anchored to the supporting concrete tunnel using reversible systems; the panels would articulate with the building envelope according to the degree of sun exposure while integrating vertical and horizontal shielding elements (Fig. 8);
– Technical, architectural and energy-related retrofitting of the building envelope by creating a 'skin'; this could be fabricated by enhancing locally sourced waste materials with a pattern or diaphram that varies according to the facade's exposure to the sun; such a system would thus create an envelope with variable porosity in relation to facade exposure; it would also integrate processing waste from the steel and high-performance glass production chains (Transparent Insulation Materials – TIM), ensuring optimisation of passive systems (Figg. 9, 10);
– Creating bioclimatic greenhouses and spaces to serve as thermal buffers using components recovered from the deconstruction of the pre-existing building; these structures would rely on the disassembly, restoration and reuse of existing fixtures which had to be removed because they were inefficient; these structures are also based on the reassembly

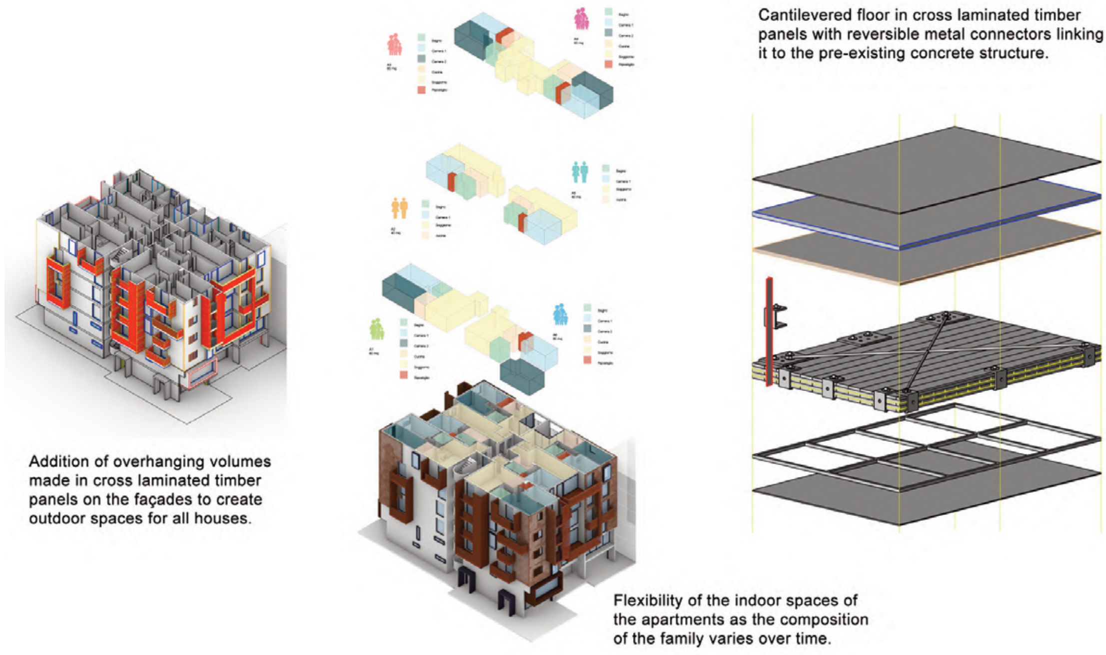
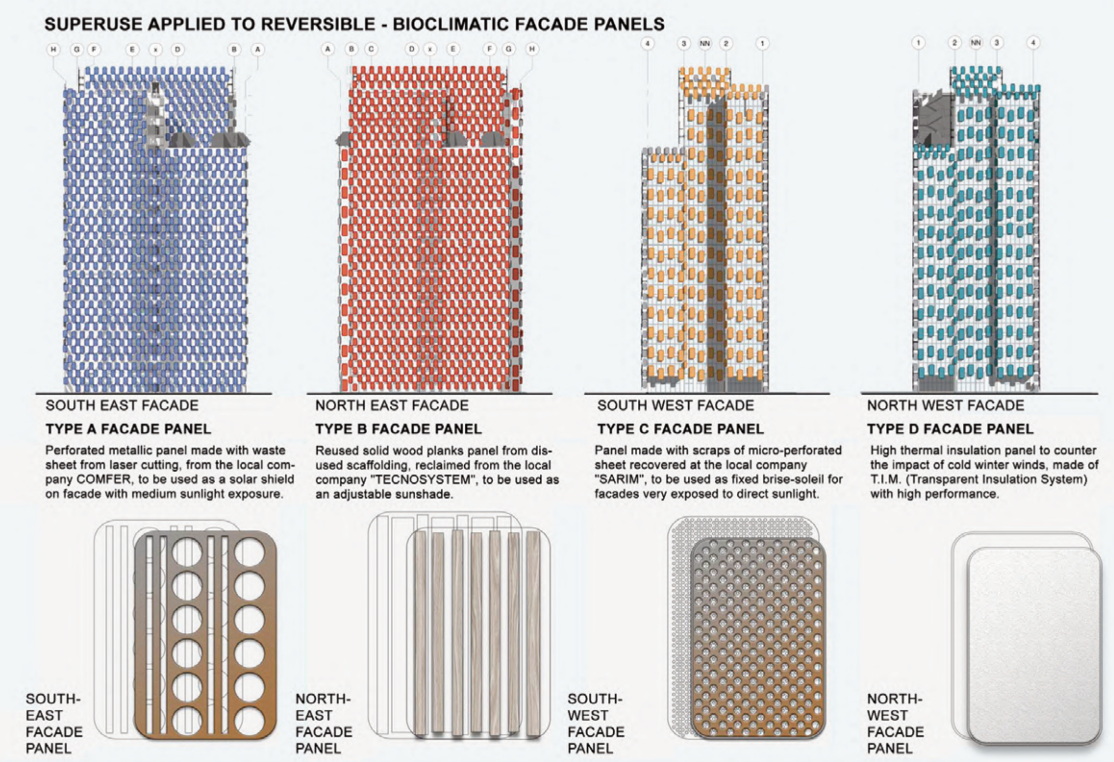


Fig. 8 | Adding external spaces to the 'Torri del quartiere di Torrevecchia housing' (Rome) proposed by inserting external overhangs using X-LAM panels and light-weight, self-supporting structures; these elements are then anchored to the supporting concrete tunnel using reversible systems; the panels, deployed on the envelope according to sun exposure, integrate vertical and horizontal shielding elements (credit: S. Baiani, P. Altamura, A. Barontini and S. Volante, 2020).

and redesign of the metal parapets removed from the facades; the integration of these steel components into the floor construction creates two types of differently shaped bioclimatic greenhouses with similarly effective passive operation (Figg. 11, 12).

Discussion of the results and research limitations | The design actions carried out in the former IACP housing in Torrevecchia in Rome reveal different facets of the research methodology as applied to the redevelopment of public residential buildings in early obsolescence. Different scenarios and levels of intervention (extensive, intermediate and light) were defined. These scenarios are coherently aligned with the existing structure's highly complex support system which is ostensibly limited in terms of flexibility and integrations. The building also does not comply with current standards or meet the needs of the people living there.

This research allowed particular investigation into deconstruction methods allowing component reuse. It also afforded case-by-case evaluation of the potential for component reuse and redeployment while paying attention to how to connect materials to the existing building. This permitted verifying the applicability of the guiding principles and requirements, 'gauging' intervention actions across various levels and evaluating the efficiency of newly designed systems. The potential drivers (Morgan and Stevenson, 2005) that favour adopting a DfD approach are clear. These include the obvious impacts in terms of reducing raw material extraction and landfill disposal as well as concomitant economic and environmental benefits. On the other hand, there



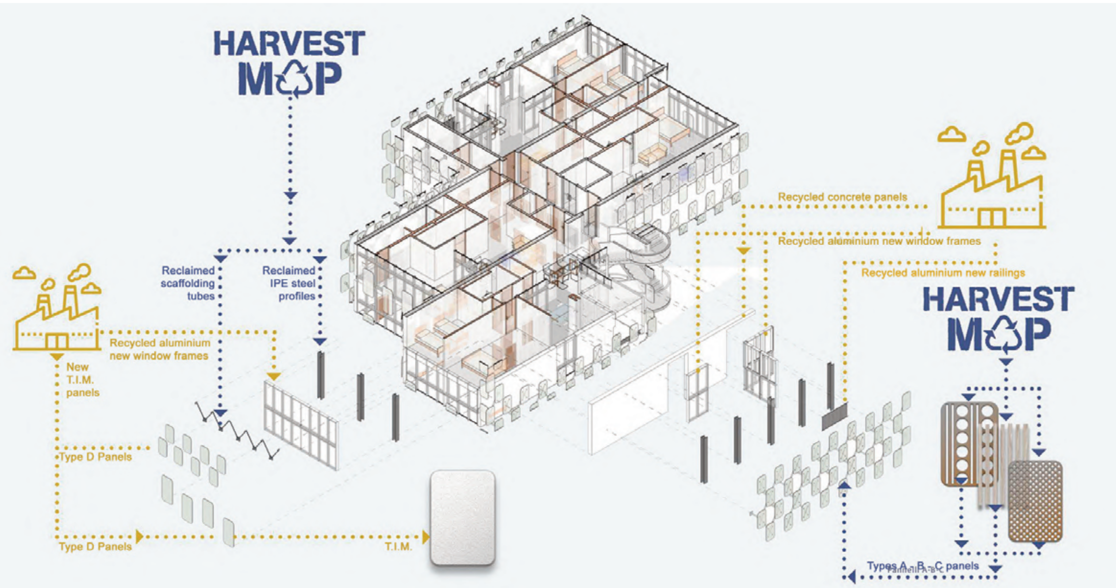


Fig. 9 | Intervention on the building envelope on the ‘Torri del quartiere di Torrevecchia’ (Rome), using lightweight panels made out of metal waste materials. The system has variable porosity adjusted to facade exposure: panel A | shielding system; panel B | adjustable shading system; panel C | strong shading system; materials were sourced from a high-performance glass supply chain (credit: S. Baiani, P. Altamura, L. Felicioni and G. Grossi, 2020).

Fig. 10 | Process of deconstructing and then integrating the reused panels with differential porosity; they are used to shield the differently performing facades; the materials were identified using the Harvest Map created for the area around the Torrevecchia site (credit: S. Baiani, P. Altamura, L. Felicioni, G. Grossi, 2020).

are limitations to note as well. Regulatory indications are restricted and do not cover the deconstruction phase of the building process. This poses difficulty in terms of gauging the effects of construction market innovations on related supply chains as currently called for in Europe. Such changes, might, in fact, promote new professional skills and differentiation in re-manufacturing processes.

From a technical point of view, other barriers emerge that limit recovery potential from the start. This is due to the complexity of the connectors used in prefabricated systems which may reduce the possibility for component reuse. There are also problems due to storage and handling which may result in a preference for lower-cost new materials over recycled ones. Above all, limited knowledge on technological alternatives to traditional concrete or steel has led to difficulties in the acceptance of mixed systems. This limited knowledge is also linked to the need for a better understanding of new modes of procurement and re-manufacturing.

From the point of view of achieved effectiveness levels, the results were measured in terms of quantitative indicators. These confirmed the methodological research choices and investigations undertaken in the Torrevecchia case. The resulting insights were as follows: 1) the share of demolition materials recovered by weight exceeds the 90%-level. In the case of the concrete panels to be removed, 100% recovery is achieved under an optimal scenario. This involves 10% on-site reuse of this material, 45% on-site recycling and the remaining 45% being sent off-site for recycling; 2) recycled/recovered materials comprised 20% overall of all intervention materials, but this percentage was higher for some specific materials (metal, wood); 3) disassembled materials and components comprised 70% of all intervention materials by weight; 4) materials came from within an extremely small radius of from 5 km to 50 km away from the site. In fact, some of the materials were 'zero-km' ones obtained via on-site recovery; 5) the level of embodied CO_2 was maintained by preserving an expected 50% on average of the existing building; 6) the level of embodied CO_2 during the intervention was also reduced by 15% to 20% on average through the use of recovered and recycled materials.

Conclusions and research perspectives | This contribution offers a point of view which, although well-anchored in the most advanced international research and design experiences, also opens up some innovative perspectives. These have grown out of the applied experience of transferring Reversible Building Design to existing buildings. In doing this, we consider the specific logic of national and, above all, European level construction systems within specific housing sectors such as public housing. In this context, the up-cycling needs of the built place suggest a common urgency to pay attention to this issue at the international level.

The positive impact of the present contribution resides in presenting a synergistic vision which draws on circular strategies of action focused on an existing structure. This made it possible to identify important technological approaches and options and building a reasoned, verified, measured and updated knowledge base aligned with current investigative advancements. The framework considered makes it possible to validate some operational choices. This, in turn, brings the various players involved closer to engaging in an innovative and complete building process in line with the circular and integrated vision guiding our activity.

This research contributes to the strategic development of low-energy/low-cost solutions aimed at circular reversible building. It also promotes innovative options in terms of regeneration activity guided by a circular perspective. It further involves introducing superuse, reuse, re-manufacturing, up-cycling and recycling of materials and building components. This strategy, in turn, also addresses the need for quality and eco-compatibility as well as increased collaboration among actors involved in the construction chain. The research results also help to define eco-effective materials-management methods over a building's life cycle while demonstrating the validity and replicability of the technological options applied. Such options may evolve from comparative studies or by identifying key intervention strategies for existing structures via reuse and reversible envelope systems. The results here also support systematising potential modes of application as well as evaluating their practicality in Italy in light of existing standards and the strong potential offered by urban resource flows.

The innovative nature of described investigations lies in verifying the feasibility of reuse within the actual urban sector rather than in the context of an experimental architectural project. The aim is to build a set of data that can be used by designers and added to or updated by individual users through tools such as the open-source Harvest Map platform. This platform supports the basic mapping of available material and construction resources in a select setting. This information may guide the choice of intervention methods in the future, have significant impacts in terms of innovation and create a decisive role for stakeholders. A fundamental cross-cutting aspect in all phases of research was that we chose to validate and evaluate interventions using a set of internationally-shared indicators of circularity. These indicators promote the analysis, interpretation and in-course verification of results. Data systematisation will allow building a framework of replicable and applicable solutions as results continue to be refined.

Prototyping the different envelope options using additive production (3d printing), in order to verify the technical flexibility of the choices made, represents a step forward. This also allows further assessing the feasibility, compliance and reversibility of the connection systems linking additional and existing structures as based on the different material scenarios developed. The aim is to reach Technology Readiness Level (TRL) 4[10]. A fundamental phase in validating the achieved results will involve applying Life Cycle Assessment (LCA)-based tools which are compatible with Building Information Modelling (BIM). These can be applied to the envelope system developed by drawing on locally-sourced materials noted on the Harvest Map. This will afford measuring material resource efficiency while also supporting decision-making processes. The aim is to evaluate the effectiveness and efficiency of exploiting complex

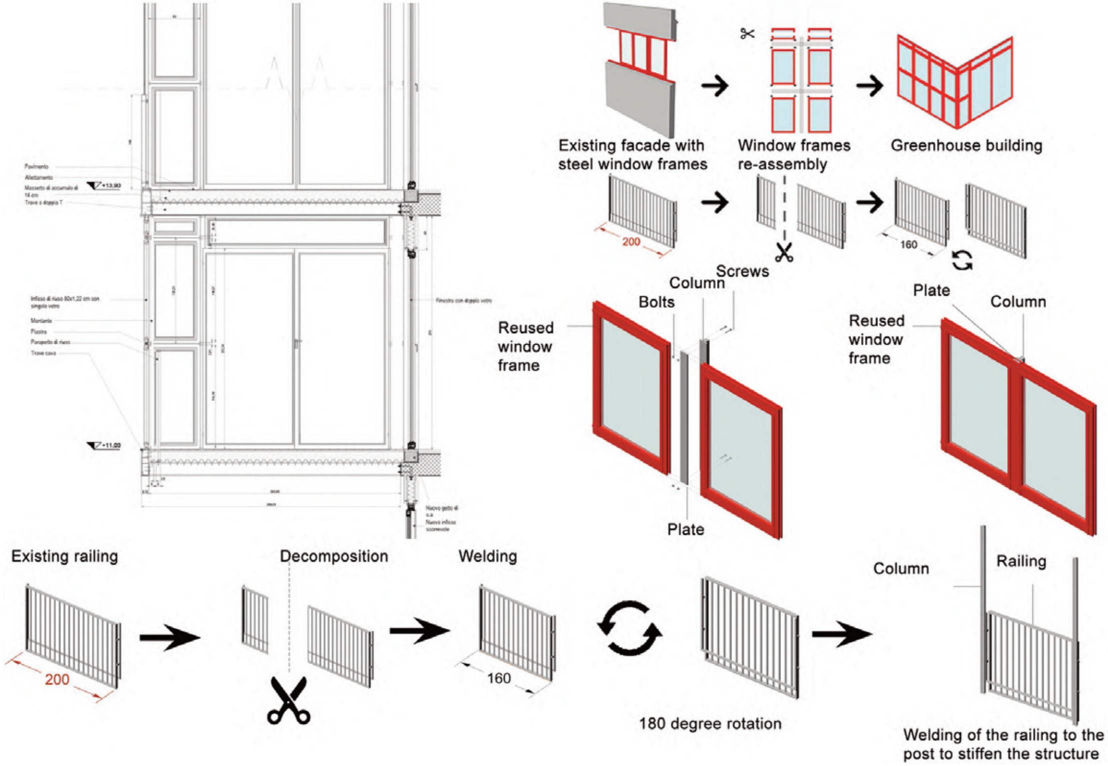


Fig. 11 | Outline of the process involved in constructing a bioclimatic greenhouse using recovered components that were 'disassembled' from the building in the Torrevecchia area under redevelopment (credit: S. Baiani, P. Altamura, N. Bonomi, E. Gianvenuti and A. Ruggiero, 2020).

and heterogeneous secondary raw material stores ('urban mines') in line with EU targets in this area. The research results will also allow expanding project-support tools systems with closed-loop building materials. This will involve integrating the aforementioned tools with those for mapping recoverable products and materials from a circular perspective. Such information may further flow into the community information system on raw materials (Raw Materials Information System – RMIS).

An expected outcome is to define a Nearly-Zero-Impact approach in terms of materials used as applied to existing structures, building processes and component production. This will further drive the development of a timely, interdisciplinary, intervention methodology which has strong applicative potential at both the national and international level. In order to ensure consistent impacts across the social, economic and environmental spheres, the research results aim for a high degree of replicability in terms of the outlined processes. Their enormous potential can also be highlighted by setting objectives that are useful to decision makers as well as supply chain operators (designers, producers, de-constructors).

Notes

1) The Research Group at Sapienza University in Rome grew out of a PhD thesis entitled 'Eco-effective Management of Construction Materials in the Life Cycle of the Building – Tools for the Pre-

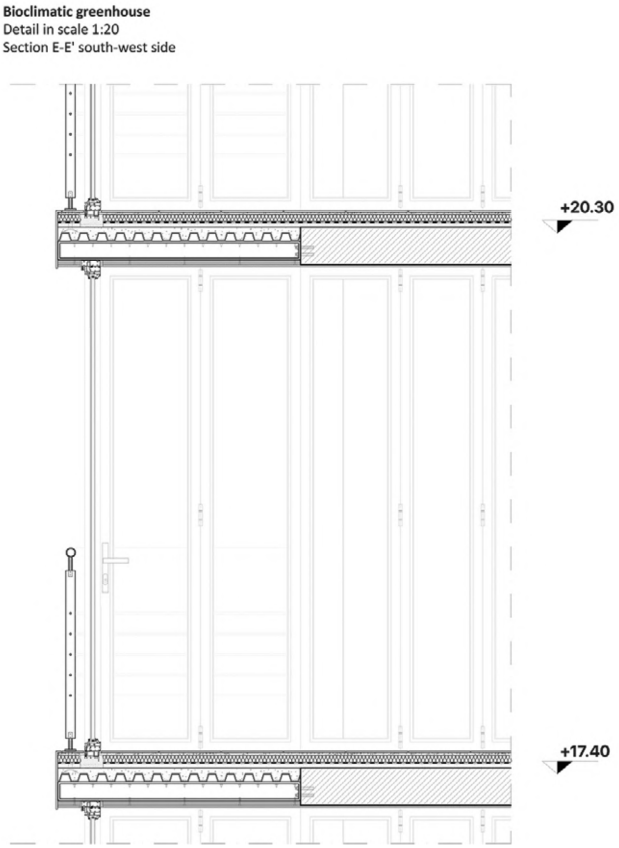


Fig. 12 | Verification of the energy performance of the bioclimatic greenhouse added to the building under redevelopment in Torrevecchia (credit: S. Baiani, P. Altamura, D. D'Olimpio, M. Avena, S, Ghadiri and M. Scacciatella, 2020).

CALCULATION OF THE ENERGY PRODUCED BY BIOCLIMATIC GREENHOUSES

SOUTH - WEST GREENHOUSE
Semi incorporated
Direct sun gaining type

	VALUE	MEASURE
Surface of the windows	8,363	mq
Frame structure surface	1,672	mq
Effective solar radiation gaining area	6,691	mq
Annual global solar radiation	442,23	kWh/mq
Collected solar energy (Qi)	2.958,96	kWh/mq
Coeff. glass transmission (t)	0,9	-
Coeff. absorption (à)	0,7	-
Amount of heat absorbed (Qa)	1.864,14	kW
Amount of heat absorbed (Qa)	1.864,14	kW
Thermal capacity of cement (Cp)	0,34	mc
Thermal mass volume (V)	63,3808	mc

NUMBER OF DAYS		DAILY GLOBAL SOLAR RADIATION	MONTHLY GLOBAL SOLAR RADIATION	MEASURE
30	novembre	2,41	72,30	kWh/mq
31	dicembre	2,07	64,17	kWh/mq
31	gennaio	2,54	78,74	kWh/mq
28	febbraio	2,78	77,84	kWh/mq
31	marzo	3,23	100,13	kWh/mq
15	aprile	3,27	49,05	kWh/mq
TOTAL GLOBAL SOLAR RADIATION PER YEAR			442,23	kWh/mq

CALCULATION OF THE ENERGY PRODUCED BY BIOCLIMATIC GREENHOUSES

SOUTH - WEST GREENHOUSE
Incorporated
Direct sun gaining type

	VALUE	MEASURE
Surface of the windows	16,767	mq
Frame structure surface	3,353	mq
Effective solar radiation gaining area	13,414	mq
Annual global solar radiation	480,92	kWh/mq
Collected solar energy (Qi)	6.451,06	kWh/mq
Coeff. glass transmission (t)	0,9	-
Coeff. absorption (à)	0,7	-
Amount of heat absorbed (Qa)	4.064,17	kW
Amount of heat absorbed (Qa)	4.064,17	kW
Thermal capacity of cement (Cp)	0,34	mc
Thermal mass volume (V)	138,18	mc

NUMBER OF DAYS		DAILY GLOBAL SOLAR RADIATION	MONTHLY GLOBAL SOLAR RADIATION	MEASURE
30	novembre	2,70	81,00	kWh/mq
31	dicembre	2,39	74,09	kWh/mq
31	gennaio	2,91	90,21	kWh/mq
28	febbraio	3,03	84,84	kWh/mq
31	marzo	3,33	103,23	kWh/mq
15	aprile	3,17	47,55	kWh/mq
TOTAL GLOBAL SOLAR RADIATION PER YEAR			480,92	kWh/mq

vention, Reuse and Recycling of C&D Waste' (lit. Gestione Eco-efficace dei Materiali da Costruzione nel Ciclo Vita dell'Edificio – Strumenti per la Prevenzione, il Riuso e il Riciclo dei Rifiuti da C&D) by P. Altamura (2013) and with E. Cangelli and S. Baiani serving as Tutor and Co-Tutor, respectively. This paper, and the cases discussed here, are the result of research funded by Sapienza University. This research has included projects on 'Closed-loop Building Materials – The Harvest Map as a Project Tool – First Application in an Urban District in Rome 2018-2020' and 'Subtraction, Addition and Insertion – Design for Reuse and Design for Deconstruction in Projects Involving Existing Structures 2020-2022'. The aforementioned research was developed by the Research Group and involved interdisciplinary collaboration supported by the 'Sapienza' Design Factory Laboratory.

2) The issue of the connector as a determining linking element stands out as the most important factor influencing a structure's disassembly potential. In this context, there are six relational models which define several different types of assembly modes: closed, layered, locked, flat and open (Durmisevic, 2019).

3) Juxtaposition, completion, addition, stratification and grafting are some of the interventions which have emerged out of contemporary debate and a balanced consideration of alterable multistrata structures which disallow adopting operational systems or rules and generalizable technical options. A number of existing public housing projects suggest how reversible additions can be combined with a low-cost approach. Some of these projects include: the recovery of 530 housing units in the Quartier du Grand Parc in Bordeaux by Lacaton & Vassal, Druot and Hutin in 2017 (Fig. 3); the transformation of the Tour Bois le Prêtre in Paris XVII by Druot and Lacaton & Vassal in 2011 (Borne, 2018; Fig. 4); and the recovery of 709 housing units in the Saint Hilaire Towers in Lormont by Lan Architecture in 2015 (Fig. 5).

4) Distinguishability refers to an intervention that may modify the original 'vision' of a structure by creating additions that fill in gaps while avoiding falsification. 'Reversibility' refers to the possibility of removing any intervention if it becomes altered or when the technology employed proves outmoded, as well as in cases where functional-regulatory adjustments are needed. In order to maintain the authenticity of an element (in terms of materials or in structural or figurative terms), the intervention must be guided by the goal of 'minimum intervention'. This aims to preserve materials, restore an overall vision and renew the functional aspects of an asset. Physical, chemical and perceptive compatibility is a cross-cutting requirement. It involves considering the material and figurative integrity of an existing element which, in turn, may be mediated by the use of new materials and technical additions.

5) Durability is the condition that a built asset, or any of its components, fulfil the functions dictated by the service environment over a specified period of time without the need for unexpected maintenance or repair (ISO 17738-1:2017). A durability scenario involves planning for the useful service life of a building and its elements, promoting a medium to long term design overview of the main construction components and considering any related maintenance or replacement cycles (GBC Italia Circular Economy Working Group, 2020).

6) Adaptability is the ability to change or modify a product, system or module, rendering it more suitable to a particular purpose (ISO 6707-1:2017). An adaptability scenario provides for extending the overall useful life of a building. This is done either by facilitating the continuation of its intended use or by designing and building flexible construction systems that allow the transformation of in-use spaces (GBC Italia Circular Economy Working Group, 2020).

7) Selective deconstruction is a systematic approach to removal which facilitates the operable separation of components and materials. This is done in order to plan disassembly interventions and their associated costs. It also provides for recovering as many intact, undamaged, uncontaminated, adjacent materials as possible and maximising their potential reusability and/or recyclability (UNI/PdR 75:2020).

8) These requirements are linked to the various levels of intervention and are identified for each system and component. They include: spatial distribution structure (adaptability); supporting structure (chemical, physical and perceptual compatibility); stratification of the envelope (separations based on the useful life of the components and materials); access to components (manoeuvrability); assembly (parallelism); connections (reversibility); quality of components (durability); materials (recyclability); casings (substitutability at different times); and operating systems (disassembly).

9) The main database used for evaluating embodied carbon is the Inventory of Carbon and Energy (ICE) by Geoffrey Hammond and Craig Jones, available at circularecology.com/embodied-carbon-footprint-database.html [Accessed 16 March 2021]. More specific values in terms of national production are found in the product sheets in Giordano (2010).

10) Prototyping will take place at the Modelling and Prototyping Laboratory of the Faculty of Architecture, Sapienza Design Factory (SDF). It will also involve contributions at varying scales from other laboratories linked to Sapienza University (e.g. the Materials and Structures Testing Laboratory of the Department of Structural Engineering and Geotechnics [DISG]) and other external partners.

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