ArchNet IJAR
International Journal of Architectural Research

ADAPTIVE BUILDING EXOSKELETONS
A biomimetic model for the rehabilitation of social housing

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Abstract
This research is an attempt to describe a new biomimetic model for the rehabilitation of social housing. In particular, the constructions built in Europe in the post Second World War period suffer of material and social degradation requiring architectural, functional and structural interventions. The analysis of the state of the art underlined the importance of the envelope in the definition of new performances and standards. Through a bio-mimicry approach, the paper shows the process leading to the definition of a building exoskeleton: a structural envelope able to solve complex sets of problems integrating different building systems. Adaptability results being a fundamental property to define an effective seismic and structural behavior but also to respond to changing user's needs and environmental conditions. In the last part of the paper, information about feasible technologies and techniques to realize the exoskeleton are presented. Finally, the conclusions show the potentiality of the model if applied in critical contexts where intensive and diffusive interventions of recovery of social housing are needed.

Keywords: *Building exoskeleton; social housing; adaptability; biomimicry; structural envelope.*

INTRODUCTION

In the post Second World War period, Europe registered the extraordinary emergence of residential districts responding to the increasing demand of social housing and to the massive destruction caused by the conflict (Turkington et al., 2004). The critical economic and social conditions led to the definition of fast construction processes and simple technologies applied to specified typologies in order to realize housing at affordable prices while on the other hand being the solution to the lack of monetary and material resources and a possibility to grant new job places also for unskilled labour (Di Biagi, 2001).

The provision of green areas and public spaces for aggregative purposes resulted often insufficient or inadequate and the critical economic condition resulted in limits to the quality of residential spaces, which in long term led to situations of social and material degradation that are progressively increasing and worsening (Power, 1997; Skifter Andersen, 2003; Murie et al., 2003). At the same time the Directive 2002/91/EU, and its review 2010/31/EU, indicated existing building heritage as a fundamental sector to obtain the reduction of energy consumption and of atmosphere pollution: new technical and technological standards for social housing buildings characterized by low energy performances, bad technical devices and inappropriate comfort standards are a primary requirement.

Another important factor to take into account is that until most recent ages, social housing buildings did not require to respond to any particular regulation in terms of seismic prevention and protection, while today many European countries necessitate considering horizontal seismic loads as fundamental to define the structural behaviour and condition of a construction. These considerations showed the necessity to apply an analysis process for social housing with an integrate approach considering architectural, structural and functional characteristics.

Problem definition

Innovative standards for the quality and safety of living spaces are required by the new regulations in the field of seismic engineering and by the principles of economic, social and environmental sustainability. A fundamental phase of urban requalification is to apply this requirement to the process of recovering of social housing quarters, today seen as areas of "no-excellence" promoting a process able to act at different scales from maintenance, to repair to rehabilitation and that can involve all the elements of a construction (Harris, 2001).
Structural and functional interventions are of primary importance to solve problems of safety and to improve the performances of the building but in order to solve the aesthetical degradation, the architectural *remodelage* (Castro et al., 2005) of the features of the buildings needs consideration.

Although architectural requalification is often an interpretative process (Snodgrass and Coyne, 2006) in which it is important to identify the permanence elements and the features to enhance or to replace with the use of new technologies and materials, in this historical period of economic and energetic crisis, energy saving, reduction of the detrimental emissions and resources preservation are primary goals. In opposition with the tabula rasa concept there is the necessity to preserve materials and objects that at the same time must face the necessity of a deep restoration process for the existing social housing. In order to transform the residential districts from a critical part of the city to a strategic resource to revitalize it (Grecchi, 2008), it is necessary to develop new design concepts and conceptual methods in planning interventions on social housing, one of those will be presented in this paper.

Research question

The research analysed the feasibility of a new approach for the renovation of social housing, to be applied independently from the typology and technology of the construction and from the site condition and location. Classifications and study of the state of the art for social housing and rehabilitation of residential building were fundamental to define the strategies of action and the approach led to the definition of a model with the objective to answer to a complex set of problem with a single integrated construction element. This study considered the complex situation of social housing heritage and its requirements in terms of seismic and energy retrofitting and architectural interventions thus investigating the effectiveness of developing an integrate approach in between of civil engineering and architecture and, for this reason, the combination between different needs and considerations progresses in parallel using different tools and design methods.

Scope of the paper

The paper considers technologies, typologies, structural behaviours and architectural features related to the social housing constructions built after the Second World War and located in a European contest. The buildings are considered using an integrate approach (Lovell, 2010) of different building systems seen as part of a multi-layered construction (Brand, 1994) while the biomimicry approach (Pawlyin, 2011) is used to define the building exoskeleton, its properties and its characteristics in relation to user's need and environmental conditions.

OBJECT AND OBJECTIVE OF THE ANALYSIS

The objective of this research is to introduce new urban and architectural qualities, better performances in building heritage and in this way to obtain a greater rate of satisfaction of the users. Considering that the objects of this analysis are buildings characterized by inadequate and obsolescent aesthetic features, the research project, referring to the principles of the biomimicry (Pawlyn, 2011) suggests interventions based on the application of a new external structural envelope that will be called 'building exoskeleton'. In the animal world, the exoskeleton is external, light and resistant armour connected with other apparatuses and its role is to protect the internal areas of a body from external input such as excessive sunlight and temperature or impacts and attacks. In this way, the exoskeleton performs a very complex set of roles from the structural to the thermal, from the aesthetical to the functional (University of Bath, 2008).

Since in an ecosystem the resources are limited, Nature uses a variety of shapes to maximize the efficiency of an element using the minimal amount of material because so, for example, in a human skeleton, bones increase their section where higher strength is required and in this way greater strength is reached with a relatively small increase in weight. From a structural point of view, if we think about new constructions, the strength-weight ratio is fundamental to reach the optimization in the use of materials and the defined “building exoskeleton”, as an enclosing capsule, can protect and support the existing building, while preserving and enhancing performance, safe and safety, seismic behaviour and aesthetic quality. So this research paper has the objective to present a conceptual model of a seismic and adaptive exoskeleton for the requalification of the social housing buildings lacking of aesthetic, morphological and architectural values to translate it in a physical model, showing the process applied for the definition and the tools and methods used for the interpretation of the data.

RESEARCH METHODOLOGIES

Research method

The first phase of the research corresponded to a broad collection of applications and theoretical data focusing on urban regeneration and social housing in Europe, in order to underline different approaches and techniques applied by architects, engineers and urban planners. The choice of a qualitative method for the collection and analysis helped to detect the cultural and social aspects hidden behind the dimension of the built environment, using different types of resources and interpreting them throughout definitions, perceptions and opinions established directly by the researcher in different steps during the research (Denzin and Lincoln, 2000).

Indeed, it is demonstrated that the personal and subjective aspects of the data cannot often be detected using quantitative methods (Kaplan and Maxwell, 1994), losing and sometimes mislaying the full understanding of the existing phenomena in their real context (Yin, 1989). Among the qualitative methods, the “case study method” was used in order to obtain broader and more comprehensive definitions able to lead to further generalizations (Yin, 1993), starting from existing interventions and previous studies about social housing that were classified as in the following paragraphs. The collection and analysis of the data was conducted to the extent of a “theoretical saturation” (Glaser, 1992), with the double objective to have not extra or repetitive information and to avoid missing data in the required field of research, referred to approaches to regeneration of social housing applied in Europe.

Design method

Design often meets problems and challenges that Nature already solved in order to preserve the equilibrium and that, if correctly interpreted by critic emulation, can lead to new technologies and innovations: the idea is that a not effective design leads to the extinction of the product, so what today we can find in Nature are the successful models. However, the biomimicry design method does not only look for solution in the Nature, but it also tries to emulate its practices where sustainability, for example, is the result of bottom-up processes, optimization, diversity, adaption and evolution, shapes and materials. The classification system used by the biomimicry approach is called taxonomy and it is defined by functions and strategies: functions are the challenges while strategies are the solution found by Nature to solve them. If applied to this research, the animal exoskeleton can be one the strategy applied by the Nature to respond to a complex set of requirements, concept that will be further explained later.

The chosen route of the biomimicry design method applied in this research starts from a challenge, the renovation of social housing building with seismic, energetic and aesthetical problems, finding a solution in the biological world, the animal exoskeleton.

MAIN FINDINGS

Collection of the data about European social housing

The collection of the data related to European social housing in the post Second World War period, led to the definition of an analysis method with a classification into different categories:

- Society: this parameter gives a connection between social degradation of the areas and material degradation of buildings and spaces.
- Architecture: some social housing buildings represent an important cultural heritage for cities and countries because of their scheme or because of the architect that designed them. It is fundamental to recognize what to preserve and what to alter.
- Structure: the analysis of the structural behaviour of the existing buildings is strictly connected with the study of the typology and technology applied for the construction. Some schemes appeared in many occasions but always with some important variations. To develop a strategy to solve seismic problems it is necessary to know the structural condition and behaviour of these buildings, with all their differences and their characteristics.
- Performance: this category expresses both of the relationship between the building and the environment and between the building and the user. It is fundamental to know technical data connected with building physics but also with user comfort to develop a new strategy.

Renovation strategies applied to social housing in Europe

The study of the state of the art in this field led to the individuation of different strategies applied on the building heritage. These approaches relate with the type of obsolescence observed, which can be figurative, structural or functional (Malighetti, 2011). The classification proposed in this paper, result of the case study method, shows a first division between strategy of addition and strategy of subtraction with a series of subdivisions, which indicate different approaches, which act from the small scale to the scale of the building. The analysis underlined also the possibility of coexistence of different techniques within the same construction.

Addition: the new part adds and combines with the existing elements, which are substantially preserved.

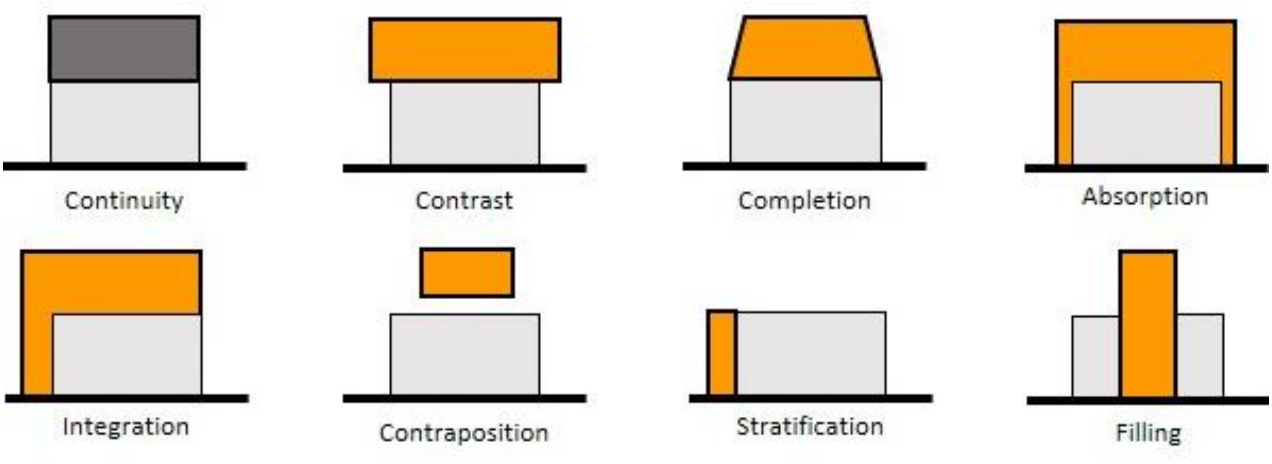

Figure 1. Strategies of addition applied to social housing (Source: Author).

- Continuity: the new part presents no sharp breaks in the logical figurative sequence of the existing building in terms of shape, dimensions, architectural features, colour or material.
- Contrast: the new part presents strict differences from the existing building in terms of shape, dimensions, architectural features, colour or material.
- Completion: the new part is an element that completes the image, the perception or the characteristics of the existing building.
- Absorption: the new part covers and absorbs the existing building or, vice versa, the new part is contained in the volume of the existing building.
- Integration: the new part and the existing building with substantially different features collaborate and integrate to shape a new image for the construction.
- Contraposition: the new part acts as a counterbalance for the existing building creating a new equilibrium in the overall perception.
- Stratification: the new part is a surface element able to change the architecture features or the performances of the envelope or of a part of it.
- Filling: a new volume or surface fills the gap between two or more buildings or between different parts of the same building.

Subtraction: the new part finds place in the existing building subtracting some element or some characteristic of it.

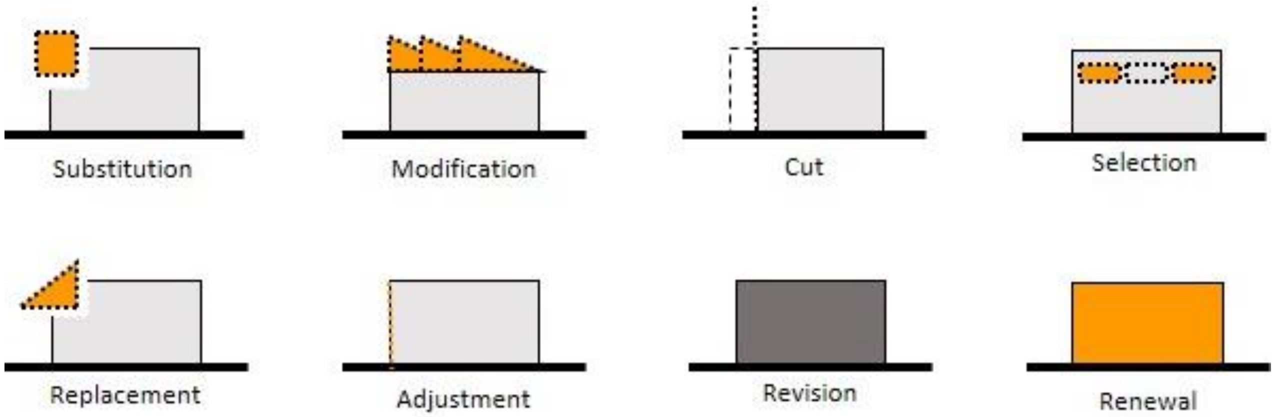

Figure 2. Strategies of subtraction applied to social housing (Source: Author).

- Substitution: the new part substitutes a part or an element of the existing building, its function, its characteristics and its performances.
- Modification: the new part modifies and replaces some of the characteristics and of the features of the existing building.
- Cut: the existing building is subjected to a sharp cut of one or more of its part accordingly to the design of the new part.
- Selection: some elements or some parts of the existing building are removed accordingly to the design of the new part.
- Replacement: the new part replaces a part or an element of the existing building with the same function but with different characteristics and performances.
- Adjustment: the new part acts as an element of adjustment and correction of some characteristics of the building previously removed.
- Revision: the new part revises the features of the existing buildings replacing them with new elements that are coherent with the previous ones in terms of characteristics or aims.
- Renewal: the new part operates a conversion in the characteristics and aims of the existing building replacing some of its elements.

The analysis wanted to be exhaustive in terms of possible methodologies of intervention applied on social housing highlightening the leading role of the envelope and its parts in defining new characteristics, performances and appearance of a construction. The envelope can be interpreted as a liminal space between inside and outside thus regulating the relationship between the building and the environment but also between the building and the users.

The envelope is also able to determinate climate control, energy performances or aesthetical values and architectural characteristics and to determinate or to influence structural stability of the building in relation to the technologies applied (Lovell, 2010).

Integration of building systems

Architectural, structural and functional considerations are necessary to develop a new strategy for the rehabilitation of social housing (Souza Cruz, 2013) and the complex of set of information to coordinate required the introduction of different methods of definition of building systems from literature. In many cases, the definition of the building systems refers to the possibility to perceive a building as a set of different layers with different roles and functions (Brand, 1994) so; for example, Howard Brand (1994) individuates six different layers corresponding to the foundation, the structure, the exterior envelope, the interior partitions, the mechanical systems and finally the furnishings. Richard Rush (1986) sees the building as the interaction of only four different systems, namely structure, envelope, interior and mechanical and, considering both definitions, the Jenny Lovell's idea (2010) is to obtain a deeper integration between characteristics and properties and, consequently, between the different building systems. So for instance, the envelope is able to define performances of the building but also to determine its architectural quality while the structure is able to sustain the building in different load conditions and to determine different rates of safety for the users in relation to the material used, scheme selected and external loads.

Integrating envelope and structure in a unified physical element sharing the same space it is possible to solve with a unique building system a complex set of requirements. The result of this analysis of the literature was the identification of the structural envelope, a building system responding to many different tasks, as a possible conceptual approach to apply to social housing.

The biomimicry approach

A more specific characterisation of the structural envelope was defined using a biomimicry approach (Benyus, 2002). There are different possible approaches to biomimetic design and any different approach can lead to different solutions with different rate of optimization and sustainability and it is also demonstrated (Reap et al., 2005) that biomimetic approach will not necessarily result in a more sustainable and effective solution.

In this paper, biomimicry is seen as a source of innovation in the definition of a new design concept (Baumeister, 2007),so with a given set of problems and requirements, the question was to match those to living organisms needing to solve similar issues: it is the design looking into the biology to find a corresponding model.

The result of this analysis indicated an answer into exoskeleton of insects, which gradually adjusts changing thickness, stiffness and proprieties to respond to different strains and loads.

"In their rigid state exoskeletons are stiff laminated composite structures made of chitin fibres embedded in a highly crossed matrix. The exoskeleton acts as a detector of displacement, strain or load via special organs called *sensilla*, which are partly integrated into local sections of exoskeleton. These organs amplify the information for the main detector organ, which is connected to the nerve stem. The local information obtained is used to modify the exoskeleton by changing thickness, stiffness and fibre orientation depending on the situation" (The University of Bath, 2008).

The exoskeleton defines also external appearance and thermal regulation adapting to environmental conditions, so it has all the architectural, functional and structural properties that can describe a structural envelope.

The biomimicry approach underlined also a new possible issue to take into account: the adaptability in order to make the exoskeleton able to adjust and modify in the time in order to respond to the growth of the insects. This propriety has been exploited for the definition of the new model because requirements in terms of spaces and functions can change over the time causing the premature obsolescence of a building or user's dissatisfaction. The effectiveness of the process of recovering of social housing is demonstrated not just in relation to improvement in structural and functional behaviour of the building but if it is able to define new living spaces satisfying user needs (De Rossi, 2004).

Feedback and "plus" phase

User needs can translate not only in physical necessities but also to the perception of the space and the building where they live (De Rossi, 2004) and positive opinions about the social housing complexes were typical in the years of their construction (Murie et al., 2003), when they were considered attractive living areas.

Today, although the long list of problems (Andersen, 2001), inhabitants still feel a sense of belonging to social housing districts independently their degradation, as preliminary surveys realized by the University of Trento (Italy) and the University of Brescia (Italy) highlighted an unexpected reticence among inhabitants about changing the architectural aspect of the buildings was registered. The capacity of adaption of the exoskeleton of insects guided to the definition of a strategy to solve the problem: the idea is to provide the existing buildings of a "plus" in terms of spaces and functions. In this way, the attachment and the reticence of the inhabitants to the place are solved increasing the economic value of the flat and making the spaces adaptable to changing conditions over the time (Zambelli, 2004). This technique is able also to create a cost effective approach: the existing building is preserved to avoid the waste of material resources and the energy consumption and at the same time, the cost of construction of the new external exoskeleton is balanced by the increased values of the construction and of its spaces. This phase underlined the importance of a feedback for the proposed recovering model both in terms of money than in terms of user's perception.

FINDINGS

The study of the state of the art and of the literature highlighted the possibility to apply many different approaches also in situation that can appear similar in terms of site and material conditions since different political, cultural and social realities can lead sometimes to an opposite interpretation of the existing heritage. Although the variances, it is also possible to observe how European idea of building rehabilitation in the field of social housing refers to construction techniques different from the ones originally used to realize the building and usually based on lightness and flexibility principles, with the possibility to obtain reversible and removable interventions.

The objective of most of these schemes is to modify the relationship between the building and the environment, both in terms of energetic behaviour and in terms of architectural features, and to enhance the relationship between the building and the users in terms of comfort and satisfaction. For this reason, another common constant in European practice is to apply improvements through the modification of the building envelope that is indeed the element of transition between inside and outside and consequently the one regulating interactions. Additionally, when seismic retrofitting is also necessary to grant safety for the inhabitants, a structural envelope is the model able to solve the complex set of problems and the biomimicry taxonomy showed that the exoskeleton is the biologic element that better describes a behaviour ranging from structural to architectural and functional fields. The exoskeleton, encapsulating the existing building, preserves its materials and the structure giving an effective solution in terms of costs and energy consumption for the construction process.

This new structure can be designed to have an adaptive behaviour so that in static condition it can be structurally independent from the existing building, which consequently has no to carry additional loads. On the other hands, when load conditions require additional strength such as during an earthquake, the exoskeleton activates and starts to collaborate absorbing and dissipating energy in order to prevent the collapse of the construction. This structural behaviour can be defined "intelligent" because it is able to recognize external input and to act consequently obtaining different outputs.

The adaptability property is referred also to the fact that the exoskeleton can be designed to house new spaces and functions of different dimensions in relation to changing needs of the users enhancing the economic value of the single flats and of the whole construction.

To solve the complexity of social housing field, it is necessary to define a unique model able to grant fast construction process and economy but without any restriction about the architectural features, giving the possibility of many different options and of the variety needed by different cultural contexts in terms of technologies and typologies. Repeatability and simple base elements, modifiable in relation to different real conditions, can be the key points to design easy and simple to apply while a frame structure can confer the adequate simplicity to allow a free scheme for building physics and freedom in the definition of the architectural features of the building. To determine geometrical and technological characteristics of the elements is fundamental to define the structural interaction between the new structure and the existing one and to generalize its effectiveness to a certain number of real cases where the junction is indeed the crucial element of the design because it influences the structural behaviour of the whole construction and its effectiveness. The requirement of the model and the objective of material optimization indicate the use of smart materials as a feasible solution to create the element of interaction and junction between the new and the existing structure since they are materials able to respond to a stimulus adapting to external input with a predictable and fixed action.

Among those, shape memory alloys have been studied for seismic protection (Castellano et al., 1997) in relation to their pseudoelesticity or superelasticity, an elastic and reversible response to an applied stress allowed through a phase transformation between austenitic and martensitic phases of a crystal. Shape memory alloys can grant a different range of responses in relation of different load conditions but always returning to their previous shape after the removal of even relatively high-applied strains. A superelastic alloy deforms reversibly when mechanically loaded creating a stress-induced phase but when the load is removed, the new phase becomes unstable and the material regains its original shape without any change in temperature. Since shear resistance in brickwork can be increased applying pre or post compression, shape memory alloys can be used in form of ties or cables able to respond to different external load conditions in different ways. These types of devices demonstrated to be effective in relation to building heritage (Castellano et al., 2000) to prevent the collapse of the façade of the churches or the flexional collapse of towers.

CONCLUSIONS

Social housing in Europe needs of important interventions to solve material and social detrimental conditions but it is also fundamental to preserve the existing building heritage in a period of economic and energetic crisis. When aesthetical preservation is not a concern, it is possible to develop strategies able to solve a complex set of problem using an integrate approach between different building systems and defining a structural envelope that, using a conceptual model taken from biology can be called 'building exoskeleton'. The visual perception of the building and of the residential district results completely modified by the application of exoskeletons nevertheless granting freedom in terms of dimensions, extensions, typologies and technologies while same basic common characteristics are able to define a unified code to obtain fast construction process and reduction of construction costs where extensive interventions are needed.

At the same time it could be possible to enhance the economic value of the buildings, thanks to the adaptability and reversibility of the operations planned, based on dry construction processes, that confer also a longer life span to the building in relation to changing conditions in the inhabitants or the quarters. Despite these considerations, in some of these social housing districts structural intervention against earthquakes is still the main concern even if seismic retrofitting is a relatively new field of experimentation for engineers, requiring complex technical, economic and social considerations with new challenges and controversial solutions. Relatively, traditional methods of seismic retrofitting act increase the load capacity of the building working on its stiffness and strength or act decreasing the demand, for example reducing the mass of the building. Both these methods are effective to some extent but usually expensive in terms of demolition, reconstruction, and construction process and occupant relocation being generally intrusive approaches. For this reason in the last years, innovative methods have been developed in order to obtain seismic retrofitting with more friendly processes as for example applying the reduction of the stiffness of the building, increasing the period of vibration and consequently reducing the seismic action, or increasing the ductility acting locally on some elements with confinement or pre-compression.

This paper and the model proposed can be instead related to the concept of damage-controlled structures (Huang et al., 2001) which consists in two parallel structures: the auxiliary structure is designed to damage and it introduces larger stiffness and new energy dissipation capacity and in this way the primary structure can resist also to severe earthquake. The application of damage-controlled model to existing buildings imposes further considerations in terms of compatibility and interaction and in this field the definition of the building exoskeleton method can open to new research and innovations in that direction, promoting light interventions acting from the outside. Future studies about building exoskeleton are also oriented towards the optimization of the design and of the use of the materials, in relation to different typologies, dimensions and proportions of the social housing buildings in order to find recurrence factors and common strategies of action.

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