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ADAPTIVE EXOSKELETON

A Methodological Approach for Retrofitting Existing Constructions

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ABSTRACT

Architectural design has to cope with the huge leap of design standards and technological knowledge, the display of an achieved development: retrofit aims at adapting past buildings to this level. New parameters are now defining the built environment: carbon dioxide equivalent, vulnerability indexes, comfort variables unknown at the time of construction of the vast majority of the European and Italian building stock. Yet, to overcome the idea that retrofit operations belong to the realm of purely technical operations, we must recognize the long history of the operation of adaptation and the complexity and cultural richness proper of technological and environmental design. Adaptation means to praise the profound, yet fragile, connection with the environment, whereby this relation is, for some reason, broken or endangered. Reuse and renovation imply an ethical commitment towards the environment as a collective value, connected to a variety of externalities, boundary conditions, limitations and expectations. It must be recognised that existing assets hold an enormous material potential in terms of embodied energy and workforce, whose life needs to be extended: only in this way their importance as traces of memory and infrastructural framework will last as a backbone for the future.

Aim of this thesis is to experiment another option for “re-cycling” buildings, even when these would reach the end of their useful life: the limit state of demolition and reconstruction, an operation whose avoidance must be pursued by any technical means. A complex design challenge, seeking for a multidisciplinary and integrated design methodology: firmly based on an adequate knowledge of the weaknesses of the specific object, radically committed to the achievement of its objectives in terms of safety, functionality, liveability and marketability. The proposed Adaptive Exoskeleton methodological approach consists in an additive strategy: the existing building is enclosed in a steel cage which, rigidly connected to the main structure, is able to consistently alter its dynamic response, making up for the seismic vulnerabilities that are common to many buildings of modernity, for instance of residential reinforced concrete multi storey frames. The promising idea of retrofitting from the outside, employing lightweight and dry construction methods, is aimed at minimising the interferences with the everyday life of the building and its inhabitants, hence the aversion and friction at transformation. Furthermore, the new envelope can drastically enhance the energy performance and allow for an upgrade of the overall degree of functionality, ultimately extending the useful life and awarding with renewed values.

The case study for this speculative design proposal is set in the southern end of Turin’s outskirts, within the district of *Mirafiori Nord*: a mid-rise residential tower, built at beginning of the ‘60s as part of an *INA-CASA* affordable housing program. The final proposal’s development is, itself, the application of a multidisciplinary approach, in fact carried out in cooperation with a master student of Civil Engineering. Following the joint experimental prototyping of a few different structural typologies and the assessment of their environmental impact, the work of this thesis aims to bring at further architectural extents these results, by physically defining the behaviour of the new envelope and energy performance of the building.

SOMMARIO

Il progetto architettonico deve oggi fare i conti con il notevole livello di avanzamento in termini di requisiti e competenza tecnica proprio della contemporaneità: il retrofit si prefigge di adeguare le costruzioni del passato a questo livello. Nuovi parametri, estranei alla gran parte del vetusto patrimonio europeo ed italiano, definiscono l'ambiente costruito: CO_2 equivalente, indici di vulnerabilità, variabili di comfort. Non bisogna però cadere nell'errore di considerare il progetto di retrofit come iniziativa di natura meramente tecnica: in primo luogo per la lunga tradizione architettonica di tale operazione, ma anche per la complessità insita al progetto ambientale e tecnologico. Adattare significa anche ricucire il mondo artificiale con il suo ambiente, un legame fragile, specialmente quando tale connessione sia per qualche motivo danneggiata o in pericolo. Cultura del recupero significa porsi con una nuova etica nei confronti dell'ambiente, alla complessità di relazioni, condizioni ed aspettative che si avvicendano intorno ad esso. Occorre altresì dare giusto valore alle qualità materiali dell'esistente, un enorme potenziale di energia e forza lavoro già dispiegato sul territorio: solo prolungandone il ciclo di vita si può garantire la loro sopravvivenza nella memoria e come traccia per il futuro.

Lo scopo di questa tesi, pertanto, è di sperimentare un'altra strategia per il "ri-ciclo" di edifici esistenti, anche nel caso in cui questi dovessero raggiungere il termine della vita utile di progetto: lo stato limite di demolizione e ricostruzione, un'operazione aberrante, da impedire con qualsiasi mezzo tecnico. Una sfida complessa, che necessita di un approccio multidisciplinare ed olistico: saldamente fondato su un attento studio delle condizioni reali, radicalmente indirizzato al raggiungimento di adeguati livelli di sicurezza, funzionalità, vivibilità e fattibilità. L'approccio metodologico Esoscheletro Adattivo consiste in una strategia additiva: l'edificio esistente è avvolto in un'impalcatura in acciaio, connessa rigidamente alla struttura primaria, capace pertanto di modificare in modo effettivo la risposta dinamica del sistema e ponendo dunque rimedio alle vulnerabilità tipiche di gran parte del patrimonio costruito passato.
La promettente strategia di agire sull'esistente dall'esterno, impiegando metodi di costruzione leggeri ed a secco, verte proprio alla riduzione dell'interferenza della trasformazione in atto con la vita di tutti i giorni, e dunque ad eliminare l'avversione che spesso riguarda queste operazioni.
In aggiunta, il ridisegno dell'involucro è in grado di sopperire alle notevoli carenze in termini architettonici e di efficienza energetica, altra nota dolente del nostro patrimonio, consentendo benefici ed una rigenerazione integrata, garantendo nuova vita al manufatto.

Il caso studio selezionato per la sperimentazione progettuale è situato nel quartiere torinese di *Mirafiori Nord*: una torre residenziale, eretta nei primi anni '60 come parte del piano INA-Casa per l'area di Corso Sebastopoli.
Il progetto è stato sviluppato in collaborazione con un laureando di Ingegneria Civile, in un'ottica di collaborazione interdisciplinare. A seguito della modellazione dell'esistente e della valutazione di alcune tipologie di intervento, il lavoro della presente tesi muove verso una più precisa definizione del comportamento del nuovo involucro e della sua prestazione in relazione al fabbisogno energetico dell'edificio.

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INTRODUCTION

00.1 STATE OF THE PROBLEM

The broken present of dwelling

Italy is aging, along with its building stock: just as the population becomes older and older, the national housing asset is gradually experiencing decay and degradation. *Istat*, the Italian institute of statistics, draws up every ten years the census of this heritage. The “bigger picture” is fairly clear: of the 12.2 millions of residential buildings scheduled, 9 (74% of the total) is older than 40 years (built before 1980). If the threshold is set to 1970 (more than 50 years of life, quite a significant value for the design of civil constructions) the percentage reaches 57% (6.9 millions).[01] Given that these data refer to the average national state, it is worth to mention that this share is often higher in major cities. For some peculiar historic reasons: the traditional diffused features of the Italian built environment, a long lasting impulse of development that, across the centuries, colonized a wide part of the national territory making of our country one of the densest of the entire European area, stops abruptly after the Second World War. As Italy enters the long decade known as the Italian economic miracle (conventionally considered coincident with the 50s, though carried on with similar modalities at least until the late 60s), the extensive urbanization plays a crucial role in the process of modernization of the new-born Italian republic. This process, overwhelming and at times uncontrolled, is strongly connected with the industrialization of the urban territory; however, just as much as the industrial growth of major cities (particularly northern ones) is the main driver of this process, its decay, starting out from the 80s, triggered the opposite phenomenon. It is only a recent fact the inversion of this trend, more precisely coinciding with the turn of the millennium, when the new thrust of service and information economy draws new interest on the city. **(Lanzani and Pasqui, 2015)**

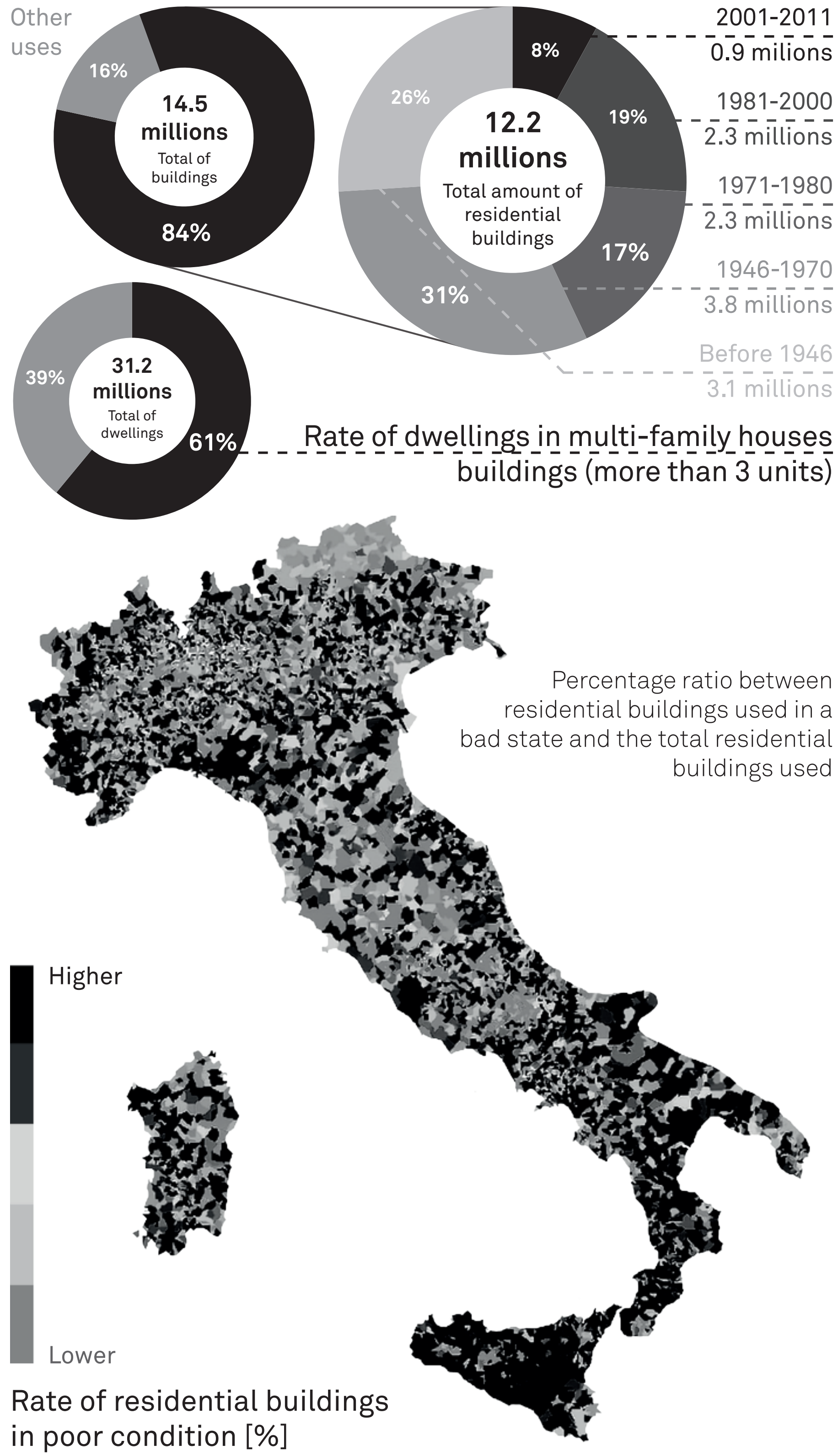
The huge urbanization of the post-war period has indeed some specific features, as well as a great relevance for the sake of this thesis. Foremost in quantitative terms: with regard to the above mentioned data sets, a closer look at the interval between 1946 and 1970 (post-war reconstruction and economic boom) validate this brief historic excursus on the Italian miraculous migration to the city and its impact on the housing condition. Of the 6.9 millions built before 1970, 3.8 are those built in this time frame, a share of about 55% of the pre-1970 and 31% of the total 12.2 residential buildings. Needless to say, almost one third of the total Italian stock, indeed a huge real estate value. Though, also the qualitative aspect plays an important role: let’s consider, for instance, the evolution of Italian regulations about

[01] Data retrieved from the 15th national census: *15° Censimento della popolazione e delle abitazioni* (2011)

Figure 01

Infographic: state of the Italian housing stock

Above: distribution of dwellings by construction period.



structural earthquake resistance and energy performance of buildings. The first contemporary Italian anti-seismic legislation dates back to 1974,[02] while the introduction of a norm regarding energy savings in the building industry happened only in 1976.[03] It means, half of the Italian housing stock was built without employing any consistent design methodology about seismic resistance and about 58% without any consideration of its energy imprint, and indeed the entirety of the buildings built in the post-war and economic miracle time interval. For, if we consider that the regulations about structural design and energy efficiency have been improved ever since, of which the latest versions date respectively to 2018[04] and 2015[05], the gap between new quality standards and these buildings appears unbearable.

Little wonder that, in the age of "The large number" (*Il Grande Numero*, title of the XIV *Triennale di Milano* in 1968), the age of mass migrations to the city, of the birth of a consumerist society, to maximise the ratio between quantity and quality became the main paradigm of development. Often regarded as an age of average increase of living standards, it was at the same time an age of vehement urbanization, most of times regardless of its backslash.

> *«The fundamental experience form which modern architecture, but especially modern town planning, equipped themselves with a constitution is that of growth, maybe the only and principal founding hypothesis of modernity: growth of the city, of the built land around it, of something new which is continuously added to what is existing, until this is suffocated, substituted, transformed and eventually negated.»*
> [Secchi, B. (1984). *The conditions are no longer the same*. Casabella, 498/499(1), pp.8]

Growth is the crucial intention of modern town planning of the post-war period, plentiful as it was of the ideal of new community, new settlement, as an attempt to impose a power on a conceptually infinite space, ultimately to dominate future. Accordingly, a progressive detachment from the physical and material realm of architecture, from the morphological shape of the city to the obsession for the economical and social structures, as a supposed intellectual framework underneath the immanent and superficial reality. **(Secchi, 1984)** A number of tangible features of housing development is peculiar of that age, all of which, at different extents, have to deal with the topic of this dissertation. Two in particular: first, the radical and widespread employment of new materials (in particular, regarding the Italian tradition) such as reinforced concrete, the industrialization and serialization of technical means of construction to allow unheard-of construction rates. **(Garda and Mele, 2019)** For, if the unquestioned application of these new methods triggered the remarkable progress of the real estate (being a consistent part of the economic miracle), the underestimation of the concern of durability and quality has recently, a few decades later, turned out to be a relevant concern. If the creation of architecture took enthusiastically part to the culture of mass production and consumption of that age, we experience now the problematic existence of countless residential suburbs in decay, a sort of "urban scale waste".

[02] L. 2 febbraio 1974, n.64, in materia di "*Provvedimenti per le costruzioni con particolari prescrizioni per le zone sismiche.*"

[03] L. 30 aprile 1976, n.373, in materia di "*Norme per il contenimento del consumo energetico per usi termici negli edifici.*"

[04] D.M. 17 gennaio 2018, in materia di "*Aggiornamento delle «Norme tecniche per le costruzioni.»*"

[05] D.M. 26 giugno 2015, in materia di "*Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici.»*"

Figure 02

Pruitt–Igoe's demolition, St. Luis (USA) (1972-1976)

Completed in 1954, the Wendell O. Pruitt Homes and William Igoe Apartments complex became tragically famous as an icon of failure of modern, post-war urban housing development.

First deficiencies showed up soon after its completion, and by the 60's it was already sadly famous for social issues and racial segregation. No other solutions were found: the entire complex was demolished.

Second, the state became the first promoter of this growth. The widespread employment of public resources for affordable housing plans, in first place the *INA-CASA* initiatives in many of the major industrial cities, mirrors the expeditious rise of an Italian welfare state. **(Lanzani and Pasqui, 2015)** The urban planning of these new working-class suburbs, although being a demonstration of a new model of territorial subjugation, became at the same time the deployment of a renewed, universal and (it was expected) stable set of social relations and interactions in form of spatial organizational structures. **(Secchi, 1984)** Again at this point, as the universal social and political order envisaged back than collapsed,[05] it is now for all to see the obsolescence of its urban and architectural organizational structure, in relation to a completely renewed urban society and community. At the same time, the public control proofed all too often unable to control the quality, especially that of private speculative developments. **(De Fusco, 1999)**

Finally, Italy is not alone. Although this process of modernization manifested later in Italy, the obsolescence in structural, environmental and functional terms of the housing stock of the post-war period is a concern of many nations in Europe: flourishing *Ville Radieuse* in France have been experiencing harsh social tensions ever since, *Siedlungen* and tower blocks of German and UK's cities are showing their vulnerability and lack of flexibility to modern uses. The problem of a broken present of dwelling in Europe is a common ground, a shared past, hence a common challenge.

> *«Mal comune, mezzo gaudio.»*
> [Italian collective wisedom]

[06] Though with early warnings in 1968, same year of the above mentioned XIV *Triennale di Milano*, having in fact earned great fame due to the social disputes that delayed its beginning, the twilight of the golden age of Fordism is complete in the 80s, and the collapse of the Berlin wall in 1989 opens up to the age of globalization.

What is there left to do? First things first, the renewed sensibility for the environment and its effect on architecture and urbanism has drastically put at end the glorious times for the modernist ideal of growth are over. The concept of a *Tabula Rasa* model of development is now no longer acceptable, since its premises would imply the existence on the planet of an infinite amount of resources, a condition that scientists and philosophers of the early days of environmentalism already envisaged as scientifically and ethically improper. With the rise of the thoughtful and environmentally aware civilization of contemporary days, this whole ideal is therefore to consider fatally over. We now talk, with right, about land consumption as one of the main plagues of a die-hard system of production and consumption, whose ideal background has its roots in the same founding principles of modernity. Land is, as a matter of fact, one of the most important resources on earth, with its crucial role of stabilizer and host for innumerable biological processes of the natural ecosystem. **(Carrington, 2019)** Though this role is currently put in danger by human activity: artificial land accounts in Europe for a 4.2% of the total surface, and this rate rises to 6.9% in Italy, a rather high degree of anthropization.[07] Particularly interesting the data about the land use rate of unused and abandoned areas: the European mean level amounts to 15.8% (again, with Italy above the average value), portraying the consequences of another contemporary phenomenon, well known to the urbanists: the shrinking city, urban land abandonment, consequence of a loss of economic or cultural interest by the urban community. **(Stohr, 2004)**

Although far from being part of the concern of this thesis, these necessary premises about the state of the art in urbanism thinking and land use planning demonstrate that a new era of urban renewal through expansion is nor desirable or tolerable in environmental terms, nor expectable with regard to socio-economic and demographic projections, at least in advanced and vastly urbanized western countries. The rising degree of obsolescence of the European building stock leaves only two distinct possibilities: on the one hand, demolition and substitution. A radical approach that, in recent decades, has found its way to become the standard for many European cities. Yet, there still exist another option: the design for regeneration, a "re-cycling" initiative at the scale of buildings, an approach that has gained much interest in recent years, although having its roots in a long tradition of architecture as a practice of transformation. **(Gregotti, 1984)**

> *«It's a matter of never demolishing, subtracting or replacing things, but of always adding, transforming and utilising them. [..] This is a work whose goal is precision, delicacy, amiability and attentiveness: being attentive to people, uses, buildings, trees, asphalt or grass surfaces, to what already exists. It's a matter of causing the least inconvenience or no inconvenience at all. It's a matter of being generous, giving more, facilitating usage and simplifying life.»*
> [Druot, F., Lacaton, A. and Vassal, J. (2007). *Plus: large-scale housing developments. An exceptional case.* 1st ed. Barcelona: Editorial Gustavo]

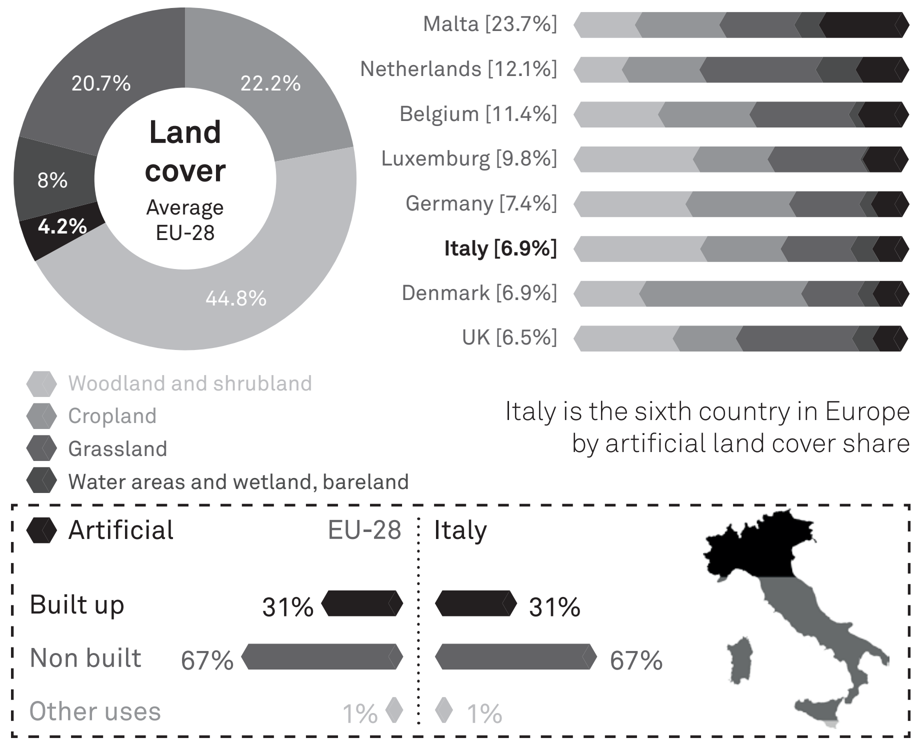
[07] Data retrieved from the *Land cover statistics*, Eurostat (July 2017)

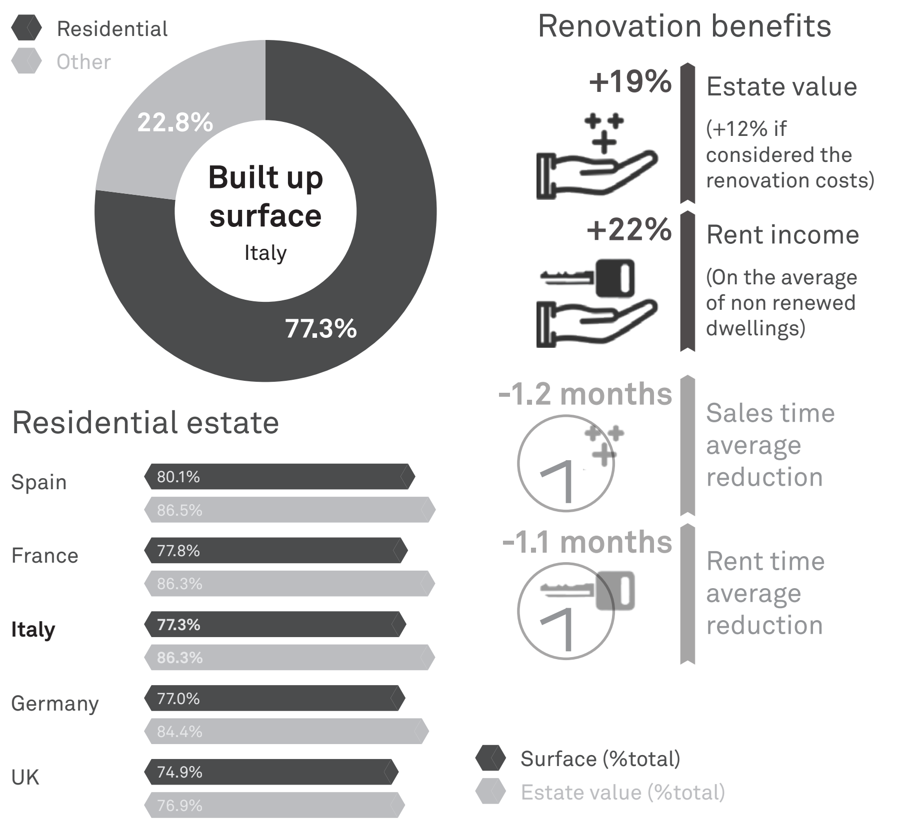
Figure 03 (Above)

Infographic: artificial land cover statistics

Figure 04 (Below)

Existing value of the Italian residential stock and potential value of renovation





Retrofitting existing constructions

The retrofit of existing heritage belongs to this latter wide cultural frame, a shifted mentality towards urban and architectural planning, one that is more concerned about the care and maintenance of what already exists. Its value can be expressed in economic terms: for instance, the Italian residential real estate is worth 3.8 times the *GDP*, about 6.227bn euros, being a consistent and essential part of the country's wealth. (Lillo, 2017) Concurrently, the problem of the obsolescence and decay of buildings makes of the European residential asset the second sector by final energy consumption (accounting for a 25.3% of the total), with a massive impact on economy and environment, considered the high rate of continental dependency on non-renewable primary sources. (Ec.europa.eu, 2019) In Italy, the final consumption of energy for civil uses rises to the 39.3%, becoming the first sector in this category. (MiSE, 2018) As another face of the same coin, the seismic vulnerability of buildings has an enormous socio-economic costs, though latent because manifested only in the eventuality of a disastrous seismic event. Also in this regard, Italy can unfortunately claim a rather inadequate degree of structural safety of the building stock, with reference instead to the average high level of intrinsic seismic hazard of the country. (Palermo et al., 2011) Though not only the economic value (and the costs of the diffused obsolescence and vulnerability) matters: right by virtue of the intriguing perspectives of the rising green and circular economies, it is now the time to reconsider also the embodied environmental value of existing constructions. Placed in urbanized and infrastructured areas, they hold at the same time a dormant potential in terms of matter and embodied energy, a potential often disregarded in traditional assessment methodologies, though needing to be restored and regenerated. (Losasso, 2012)

Within this context, retrofit is evidently the technological "armed wing" of active conservation policies and regenerative design enterprises. The word blends together *retroactive* (which takes effect from a moment in the past) and *refit*, the action of repairing or restoring machinery, equipment or fittings. All together, the conventional meaning implies the addition of components or accessories to something that were not present after manufacturing or in any subsequent moment of the artefact. (Retrofit, 2019a) Much of the popularity in the 40s and 50s of the term derives from the military industry: retrofitting became a necessity from the Second World War onwards, since the pace of technological progress made planes or ships to be out of date soon after, if not at times before, their completion. (Retrofit, 2019b) Its association to the building industry might as well be traced back to the 1973 Oil Crisis, a world class shaking event that shifted anywhere on the planet the attention on the issue of energy provision and consumption. As a matter of fact, the first regulations about energy efficiency of houses were developed shortly after the crisis: the adaptation of the existing stock became crucial. (Papadopoulos, 2011) To date, retrofit should be regarded

as a crucial European challenge on the path for a more sustainable and resilient community. Concurrently to the dare of awaking the latent potential of existing constructions, the rise of an ecosystem of urban regeneration (a change in conditions, from a culture of development to one of reuse and renovation). (De Fusco, 1999)

«Questa cultura della riconversione, riscontrabile anche nelle espressioni della più flagrante modernità, costituisce, a mio avviso, il fatto veramente nuovo della cultura architettonica contemporanea [..]. In sintesi, quella che una volta era questione solo di tutela e di conservazione è diventata una questione che riguarda l'intero campo dell'attività costruttiva, dagli architetti ai critici militanti, dall'industria edilizia ai politici, dagli amministratori [..].»

[De Fusco, R. (1999). *Dov'era ma non come era. Il patrimonio architettonico e l'occupazione*.. 1st ed. Firenze: Alinea Editrice]

It must be remembered that, among all the different projections about the future developments of the construction market, one aspect finds unanimous consent: the vast majority of future dwellings is already built. In parallel with the commitment at adapting what exists to this future, the retrofit of existing constructions constitute an intriguing occupational and professional possibility. At the same time, it is to expect a large scale restructuring of the real estate industry and market around the rise of the promising green and circular economies, that will give more and more importance to the design for repair, maintenance and regeneration of existing constructions. (Russo Ermolli, 2012)

In conclusion, two aspects are to be regarded as the main open threads of discussion around the contingency of architectural design for retrofitting. In first place, the cultural approach to transformation. There's an inherent ambiguity in the design for adaptation and revitalization of buildings, even when these would not undergo a change in their uses: it is worth sometimes the update of only certain components, the careless substitution or addition of some others to affect the architectural value of the original building. It must never be forgotten that these operations, far from being simple technical improvements, have to be carefully balanced with the needs of conservation. The risk for buildings, undergoing similar transformations, is that to be distorted or, even worse, trivialized with simplistic approaches of deference to technical regulations. (Bartolozzi, 2019) Second, and allegedly connected to the previous concern, the problem of the research for new methodological approaches, in fact being able to reconcile the legitimate necessity of conservation with the equally legitimate need for transformation. This will be pursued with the relentless research of new values that, although necessarily different from those of the past, will guarantee renewed qualities, while guaranteeing at the same time the extension of life-cycle of buildings and, ultimately, their preservation. The scope and objectives of this thesis are to be considered as part of this latter context of discussion and research.

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Structure and organization

The thesis is divided into three main parts. Each of them includes a number of chapters, picking up one specific topic, a limited field of cultural interest: though it will be hopefully possible to choose one single chapter to have an insight on its topic, each of these will be giving its specific contribution to the definition of the bigger picture. The order with which these chapters are organized within each part is dependant on a chosen presentational hierarchy, though it might be possible to start from one chapter in one of the parts and shuffle up the order within that part, to eventually give more relevance to one of the insights, or to give a slightly different point of view on the discourse. This approach was chosen to discard the ambition of defining a topic in its totality, rather by adding meanings and possible answers to some open threads of discussion of choice, as if the chapters' structure, puzzle pieces, might as well be expanded as the result of a further personal research. The first part aims at defining some facets of the challenge of retrofitting existing constructions. A challenge that, as introduced above, will be more and more key to the future urban development. It implies in first place a shifted mentality towards the environment and the now well acknowledged complexity of artificial-natural relations.

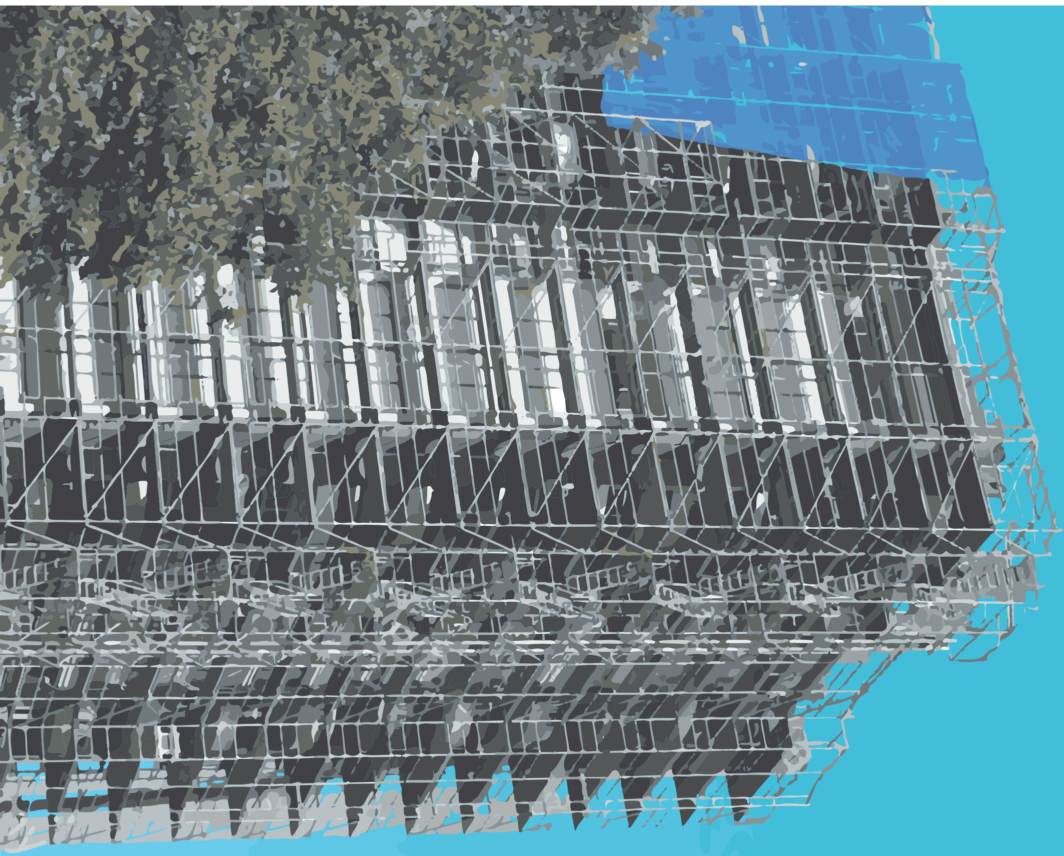
To **design for a broken present**[01.1] means in first place to shift one's attention on what exists and on the problems and weaknesses of past (physical or ephemeral) infrastructures: not only by means of a new ethical commitment towards the existing heritage, but also as a new paradigm of development, different from that of growth and sheen progress. A number of current, general concerns about the relations of technology and nature, is introduced: it is nowadays widely acknowledged the impact of man on the environment, a game-changing condition for design. Although the *environmentalisation* of the discourse around architecture led to some important results regarding the environmental quality of technologies, design should be regarded in first place a tool of repair, as some recent paradigms such restorative and regenerative design aim at being. The renewed sensibility and care for the environment brings to the front the topic of adaptation: retrieved from evolutionary biology, its ambiguity and generality are both its curse and blessing, and need to be understood deeper. Adaptivity is more and more to be regarded as a substitutive paradigm of sustainability, less static, rather referring to a dynamic and transformative process. The design for seismic resilience is, for instance, a process of adaptation to an environment. The stochastic definition of risk is a defining aspect of our reflexive modernity.

Likewise, through the scientific observation of nature, it is possible to retrieve some possible adaptive traits, such as sensitivity and redundancy, as strategies deployed by nature to provide enough adaptivity to the ever changing conditions of ecosystems. Within the context of *risk management* and *climate change adaptation* strategies, to talk about adaptive buildings[01.2] means, above all, the research for holistic and integrate approaches to architectural design, capable of reducing the friction with the constant varying conditions and hazards of the context. Adaptation is a natural process of transformation that have to regard also the built environment inherited from the past: the less invasive and demanding this process will be, the better the degree of adaptation that will be achieved. This challenge has many different facets: on one side, the research for the appropriate design methodologies to perceive this objective. Though another crucial aspect is the definition of social, political and economical boundary conditions: these shape our understanding of the built environment, define the contemporary standards and expectations about its design and trace a general path of development. A green new deal[01.3] is being defined in Europe among all the stakeholders that are involved in this process: administrators, enterprises, investors, design professionals and critique. With the circularity of processes in mind, it is important to envisage at which degree these new conditions (under construction) will affect the sustainability and feasibility of design for regeneration. The strong relevance of measures in favour of energy efficiency of the building stock, and the more recent concern about waste production and the issue of recycling building materials. Along with the rise of certification programs and Life-Cycle Assesment methodologies for buildings, a background for a culture of deep renovation is set. With particular regard to the concern of a broken present of dwelling, this problem is to be considered as a shared continental challenge, a common ground for discussion and action. Re-cycling: the future of dwelling[01.4] is an attempt, starting out from some European experiments of retrofitting and adaptation, to gather some of the new environmental, cultural, social or economic values that might have already been applied in large-scale transformations and that will eventually shape the future of housing.

The second part focuses on the presentation of the Adaptive Exoskeleton methodological approach. The definition and development[02.1] of this strategy of intervention finds an interesting ancestor in the evolution of skyscraper typologies. An intertwined process of technological and structural innovation, always oriented to the experimentation of new architectural and urban qualities within the context of a growing need for the denser and denser urban environments. High-rise construction is a compelling engineering challenge: the constant research for structural optimization led to the invention of new typologies, in particular the idea of external support frames (such as the *diagrid-type*). In the design of high-rise buildings, horizontal and dynamic forces are what matters the most: through an appropriate degree of discretization, it is possible to associate

a skyscraper to a single or multiple degree of freedom oscillator, whose relevant dynamic properties are mass, stiffness and damping. The design of these properties is the main concern of a skyscraper's design, and indeed also of the adaptive exoskeleton's seismic retrofit approach[02.2], in other words a technology transfer from the field of high-rise engineering to that of adapting existing constructions. It is in fact possible, by coupling the primary structure with a secondary lightweight frame, to control its dynamic behaviour in case of earthquake horizontal actions, hence improving its degree of safety. This approach promises to achieve this important improvement with the least interference with the existing building and its inhabitants. However, the intriguing possibilities of this additive approach do not end with the seismic improvement alone: an energy retrofit approach[02.3] might be implemented, allowing for a combined solution to both structural vulnerabilities and physical obsolescence, typical of a vast amount of dwellings in the European real estate, in particular that of the post-war period. Reinforced concrete multi-storey frames, peculiar of this era of relentless urbanisation, are now about to overcome the limit of their design life of 50 years. The Exoskeleton methodological approach can, while making up for the obsolescence in performance of existing constructions, can ultimately provide it with a new values and a new life for the integrated and sustainable retrofit of the existing heritage.

Finally, this dissertation will move towards the design of a retrofit proposal for a residential tower in Turin. Situated in the south of the city, in the suburban district named *Mirafiori Nord* (famous part of the industrial past of Turin), the chosen existing building is part of a neighbourhood built at the beginning of the 60s as part of an INA-Casa affordable housing development project. The introduction to the *INA-Casa* case study[03.1] must necessarily include the social, economic and cultural context that led to the construction of new residential towns of this sort in most of the Italian major cities, within the frame of the political and technical instructions of the *Piano Fanfani*. The construction and early life of the *Corso Sebastopoli* neighbourhood is a fragment of a bigger history, that of the Italian post-war reconstruction and of the economic and urban boom. And, indeed, from this bigger picture, some useful indications for the contemporary times might come at hand, in the expected eventuality of a regeneration of the housing stock. Introducing the Adaptive Exoskeleton approach, with regard this case study, the chapters toolkit: structure[03.2] and toolkit: energy[03.3] are an attempt to gather and organise the informations about the actual state of conservation and methods of analysis of the built object, thus supporting the design choices. As a conclusion of this process, the **final design**[03.4] is the concluding presentation of the project's result. The adequate level of graphical and technical informations about the final retrofit will show the process and final results of our retrofit proposal.



THE RETROFIT CHALLENGE

01.1 DESIGN FOR A BROKEN PRESENT

Technology and nature: broken relations

In 2019, the *Earth Overshoot Day* clocked in on July 29th, overcoming for the first time the day of August 1st, since the first recording of a planetary deficit of resources in the early 1970s. **(Earth Overshoot Day, 2019)** The concept behind the *EOD* is simple:

[EOD] *(World Biocapacity/World Ecological Footprint) x 365 = EOD*

Despite some criticisms about the objective reliability of the evaluation tools adopted to measure world's biocapacity (the ability to yearly restore the resources used on the whole earth), the inherent merit of the *EOD* lies in the simple yet effective ability to communicate a momentous message: that resources on the planet are fatally finite. In 2000 Paul J. Crutzen, the Dutch Nobel Prize for chemistry, at a conference in Mexico, uses the term *Anthropocene* to define the actual geological epoch in which human activity accounts for the major imprint on climate and geological phenomena. **(Environmentandsociety.org, 2019)** Although this concept is not new (the word itself was coined in the 1980s by the chemist Eugene F. Stoermer), it has been linked ever since with the name of Crutzen, who contributed for the most to spread the debate on this topic. Among many of the consequences of man and his unstoppable enterprise, CO_2 has to be regarded as the main human-driven factor in the atmosphere to influence the global warming. For, if the main responsible for the ejection of carbon dioxide is the combustion of fossil fuels, with distance world's favourite source of energy, no doubt left, the starting point of the *Anthropocene* is 1784, with James Watt's invention of the steam engine. **(Crutzen & Stoermer, 2002)** The atmospheric concentration of CO_2 is a simple yet effective indicator of human imprint, while one may find hard times unscrambling the mutual relations of cause and effects of environmental changes, even if the results are today for all to see. Along with carbon dioxide concentrations, the rise of average temperatures (0.8 °C up to date since 1880, two-thirds of which after 1975 at a rate of 0.15-0.20 °C per decade) **(Earthobservatory.nasa.gov, 2019)** and of mean sea levels have endangered thousands of ecosystems. Massive land and water consumption are compromising the ability of regeneration. Nor it will be possible to neglect the geopolitical consequences:

> *«[..] it is as nature and geopolitics had been conflated. [..] Who would have thought only 20 years ago that no political scientist could ignore the Earth climate system and all its uncertainties?»*
>
> [Latour, B. (2011). *Politics of Nature: East and West Perspectives.* Ethics and Global Politicvs, 4(1), pp.1-10]

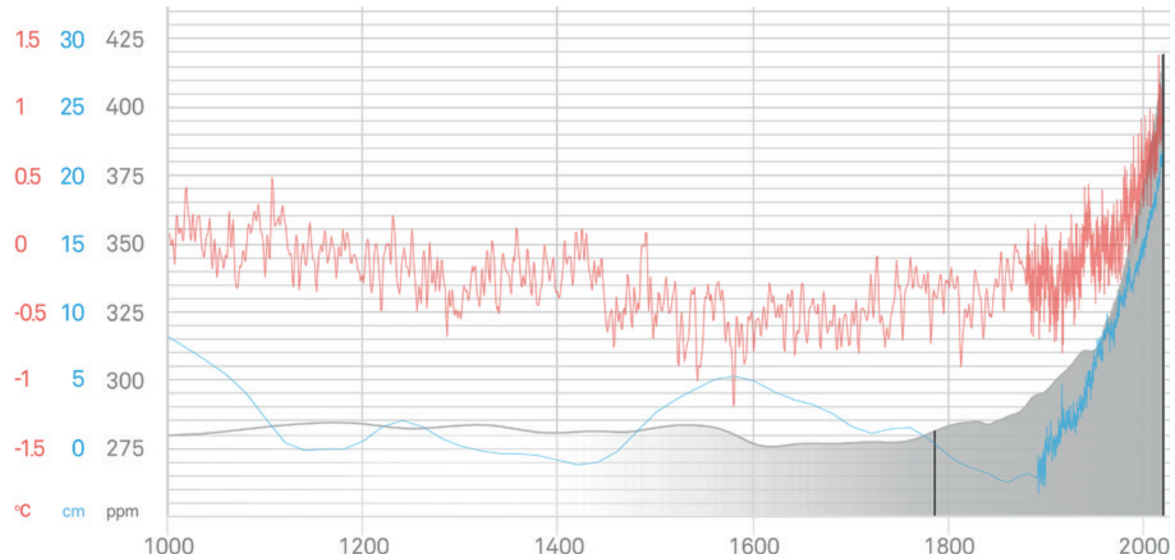


Figure 01

Atmospheric CO_2 concentrations, with temperature anomalies and mean sea levels. (since 1000 AD)

In evidence, the invention of the steam machine by Watt in 1784, notably coincides with the beginning of a hyperbolic rise of atmospheric CO_2.

The awareness of this new notion of man as a biological and telluric force, the discovery of nature's bonds and constrains returns to our conscience the image of an ill relation of man with nature, where hubris and superficiality pervade every strand of culture and progress. Likewise, it won't be possible to overlook again the impact of environmentalism on human culture, as its crucial relevance to the historical understanding of the built environment. New issues emerge to significantly influence the production and critique of architectural ideas: land consumption, energy supply, the metabolism of materials, the relation with the urban polluted atmosphere. Design is more and more taking on the role of translation of the new environmentalist knowledge of science into artefacts and behaviours. The field of architectural technology is crucial to interpret the cultural developments in architecture: for example, it would be unthinkable to understand them without considering the stress on the performance of the building's envelope, with today's in-depth parametric simulations, employment and complex visualization of data. Architectural technology is the missing link between construction, engineering and science, yet there is another aspect of growing cultural influence, the *risk factor*. **(Barber, 2016)** Anthropocene aware societies will rely more and more on a scientific and stochastic understanding of the environment, architectural projections will tend to converge with rational and statistical simulations. The relatively recent fortune of the word *resilience* happens within this cultural context, and provides an intertwined view of large scale earth changing events and natural disasters with their cultural representation. It underlines the connection between deep environmental transformations, calamities and the topic of social responsibility, such as prevention and awareness of the intrinsic risks of a particular context. Disciplinary boundaries will tend to fade: collective memory and engagement, politics, sociology, economy, material culture, each and every of these aspects is liable in the definition of the resilience's degree of a community. **(Vale and Campanella, 2005)**

By all means, the paradigm shift of the *anthropocene* is a cultural one: it is our very notion of nature to be out of date. The dichotomy nature/culture is deeply rooted and shared by many cultures, and as a widely used linguistic convention it appears to be functional and fruitful in communicative terms: it allows for a clear separation of categories and behaviours, distinct and widely accepted conventions. **(Manzini, 1990)** Though in the age of the so called *Technosphere*[01] the presence of man is fatally ubiquitous, the dividing line of what's natural and what is human blurs.

> *«[..] what is the deep meaning of the phenomena that we still define as "natural" and that we always try to place outside the anthropized world, outside the urban perimeter, outside architecture's walls. In truth, it is precisely the presence of a technosphere that seriously challenges the idea of a "natural" space as opposed to the inhabited artificial one [..].»*
> [Boeri, S. (2019). *Foreward*. In: P. Antonelli and A. Tannit, *Broken Nature*. XXII Triennale di Milano, 1st ed. Milano: Electa, p.9]

There must have been a point in history in which the relation of man with nature has been broken. This probably happened at the beginning of what has been here described as the *anthropocene*, since when nature started being considered a mere resource of consumption by man himself, when man thought it was possible to superimpose his power on nature. It is now as our present, together with its material and cultural foundations, has been broken and needs to be fixed, its relation and beliefs about nature to be rethought. Alongside, all too often we refer to the artificial in negative terms, as something that is opposed to an ancestral and atavistic "natural" state of the environment. The word *artificial* itself, conceal a semantic ambiguity: it might signify as well *false* and *not sincere*. This is a fairly recent meaning, since the origins of this word come from the Latin *artificium,* a work of art, and *artifex* produced by a craftsman, the master of one art (from the stem *ars*, that in classic latin culture implies a practical skill, a business craft). It is probably worth to mention this paradox to have a simple, yet quite explanatory picture of the contrast that human activity has undertaken with nature and the environment, at least with the advent of the industrial revolution. **(Manzini, 1990)** The evolution of these two ideas trace a history of the uses that man made of nature over the centuries. Notably, different *technosocieties*[02] rely on different ways to describe a paradigmatic duality natural/artificial. It is indeed the most important and meaningful intellectual category to have ever been conceived. **(Williams, 2004)** It regards any discipline of human knowledge: a complete history of the uses of nature should also be regarded as a history of the human thought. Although it would appear obvious that architecture belongs to the realm of artefacts, attempts to categorize architecture as nature have evolved throughout the entire course of history. In two peculiar ways, as a similitude of nature (*mimesis*) or as a part of nature itself (the myth of the shelter), at least until the scientific and industrial revolutions, when nature became few but a rational construct, a "biological metaphor". **(Forty, 2004)**

[01] *Technosphere* is a term coined by Peter Haff to describe the pervasive contemporary colonization of technological and digital infrastructures.

[02] *Technosociety*, term coined by Bruce Sterling in his book *Shaping Things* (2005), devises cultures of design and production of artefacts, whether space or objects.

[03] The metaphor that architects used to do, starting from the XVIII century, between natural and organic structures (as they were progressively revealed by the rise of natural science) and architecture. The abstraction of a structure from the matter of architecture, introduced at the beginning of the XIX century, is an example of the consequences and relevance of this metaphor.

[04] Published in 1914 by Antonio Sant'Elia

The biological metaphor[03] became of such great importance, together with the idea of abstracting structural principles from nature (whether they are intended as the building's support system or as systemic organization of technological parts and functions). The German philosopher J.W. Goethe (1749-1832) thought that this rationalist perspective was all too far from any direct observation of phenomenons. Nature is a living thing as a whole, as his research on morphology of plants points out. While the taxonomic rational system classified plants by virtue of their parts, each rigidly associated to a specific function, he rejects any classification, pursuing for an *urform*, the principle at the origin of all the living beings and their continuous evolution: the same spirit lives in the artefacts of man, that participate in the flow of ceaseless transformation of nature. He argues that culture becomes active the same moment that its survival is guaranteed, by participating in the evolutionary spirit of nature. If a building does not have a function, it will not be able to participate in the circle of life. The influence on E.E. Viollet le Duc and Luis Sullivan (1856-1924) is dramatic. Their intention towards function is fairly different from the use we understand today, as transmitted through the Modernists' use. **(Forty, 2004)** Sullivan gave birth to the paradigm:

> *«Whether it be the sweeping eagle in his flight, or the open apple-blossom, the toiling work-horse, the blithe swan, the branching oak, the winding stream at its base, the drifting clouds, over all the coursing sun, form ever follows function, and this is the law.»*
> [Sullivan, L. (1896). *The Tall Office Building Artistically Considered*, 1st ed. New York: Lippincott's Magazine, pp.403-409]

The concept of *second nature* portrayed by Goethe is indeed very influential today, as it was back then, because it envisioned, yet at the beginning of the XIX century, the core of the problem of contemporaneity. A problem that didn't regard humanity, at least until the artificial (or *second nature*) was an archipelago in a sea of nature. We know that with the industrial revolution, and at an incredible pace from the second half of the 20th century on, this ratio overturned. The result is that today our feeling is to live in an artificial world, where nature is just a "green archipelago" in a sea of artefacts. It is probably a matter of (human) scale: if we could observe things from far (or close enough, as from the space or with a microscope) we could notice how nature is still there, with its entire retroactive power. Our environment will be increasingly artificial, and it will be therefore more important than ever to consider the *second nature* and the relation that its artificial ecosystem entertains with the ecosystem of nature. **(Manzini, 1990)** The conscience that the realm of what's artificial responds to a complexity that is all in all comparable with that of natural ecosystem is fairly recent in architecture. The avant-garde of Modernism stepped back from the role of nature in the human arts and architecture, up to an absolute of rejection of nature. In the *Manifesto dell'architettura futurista*[03] it is evident a total denial of nature, envisioning a fully mechanized and artificial society: where is nature in this new world to come, what will its role be, it is not even a matter of concern. **(Forty, 2004)** Technology substitutes nature.

The result of this epochal disconnection is rather tangible in our modern cities and their environmental issues. It is from this conscience that arose the *environmentalism* movement:

«The future is here, but its impact on architecture is only just beginning. Working our buildings into the cycle of nature will return architecture to its very roots.»
[Rogers, R. (1997). *Cities for a small planet*, 1st ed. London: Faber and Faber, pp.101]

Even if the *environmentalisation* of architecture's history brought again the relation of man with nature to the fore, a complete integration of buildings and natural cycles is far from achieved, and the role of technological innovation is all too often emphasized with great optimism, whereas constantly framed by equivocal consequences. (Barber, 2018) The matter of a technological power controlling nature and social life has been a concern for historians and architecture critics since the French philosopher Michael Foucault (1926-1984): his concept of *governmentality* encompasses the rise of non-sovereign forms of power since the XVI century onward, that regards as a principle mean of power an ensemble of institutions, procedures, analyses and calculations. He was interested in how an art of social control can influence culture and everyday life. (Barber, 2009) The Danish philosopher Sven-Olov Wallenstein explains how this became the basic idea to inform the rise of modernity: modern architecture emerged when Durand, as professor at the *École Polytechnique*, transformed the Vitruvian *dispositio* from a representation of order to a tool for the ordering, regulation and control of society and environment, through the control of space in its entirety. (Wallenstein, 2009) Wallenstein's goal is to identify modern architecture as part of the *biopolitical machine*, thus acting on a *milieu* in which resource and infrastructures are entangled with social processes, and the form of management and scientific knowledge of this material conditions is, namely, architectural technology and technological innovation. The rise of a highly efficient, high-tech architectural design is based on the same principle of separation of artificial and nature, whose history has been here briefly traced, though what is different is the subjugation and subjectification of an environment, whose understanding is based on a more complex and deeper scientific knowledge. It is hardly perceivable, today, the conflict between the high level of artificiality of a contemporary high-performance building and the idea of an untouched, primitive and savage nature, as the goal of a highly technological building is to limit at a minimum standard its impact on nature. (Forty, 2004) The first era of environmentalism is part of the long rush hour of technological proliferation, which was involved by the unprecedented colonisation of the planet in the recent era of the *Anthropocene*. Whilst it certainly achieved the goal of shifting back the public interest on relations with the environment, it proofed inefficient to deal with its overall objective of controlling the quality and impact of human activity on nature, again trading off quality of this process for the remunerative quantity of uncontrolled technical innovation.

Broken world thinking

An alternative to the culture of the sheen, seamless, unquestioned technical innovation is what Steven L. Jackson calls *broken world thinking*. The world is inevitably broken: good news is that it is in world's nature to get broken over and over.

«We know, now irrefutably, that the natural systems we have long lived within and relied on have been altered beyond return (though not necessarily beyond repair[..]).»
[Jackson, S. (2013). *Rethinking Repair*. In: T. Gillespie, P. Boczkowski and K. Foot, *Media Technologies: Essays on Communication*, 1st ed. Cambridge: MIT Press, pp.223]

Jackson suggests that decay, erosion and breakdown should be regarded as dominant cultural standpoints towards nature, its uses and resources, rather than the narratives of growth and novelty. The appreciation of planet's limits and fragility, in the wake of many forerunners of conservationism and environmentalism (i.e. Rachel Carson and the intellectuals of the Frankfurt School) shifts the cultural attention away from innovation (in conventional terms) towards the infamous, daily practice of maintenance and preservation, yet crucial to keep the world going. (Jackson, 2013) Although often marginal, hidden from the mainstream culture, these activities are far from being a marginal field of human activity. Let's think of the amount of maintenance needed to keep our cities and streets operational. Not only physical infrastructures are objects of repair: media networks, lifeblood of our everyday life, rely on an extraordinary amount of care; the whole web concept evolved by means of a seamless routine of breaking and fixing, eventually heading up to new innovations. There is even a growing yet consistent concern about the care needed by social and economic systems. (Mattern, 2018) In this light, is it possible to trace a parallel history of breakdown and decay, an out of the limelight history of repair as support to the major human history of innovation? Might this paradigm be considered an epistemic advantage on the dominant myth of innovation and novelty? These open threads of discussion disclose to a new political terrain, the *ethics of care,* relating human activity with the material world in all its complexity, whether it is natural or artificial. (Jackson, 2013) According to the urban geographers Nigel Thrift and Stephan Graham, brokenness is a cognitive warn of the existence of an underground *carpet of maintenance*. Heidegger's notion of *tool-being* is based on a distinction between tools *ready-to-end*, fully functional, right where one would expect them to be, and *present-at-hand*, the broken things. Whilst one object moves from one state to the other, our attention is fatally caught by the tool's inevitable reality, and by the universe of connections that this tool involves. A true consciousness of the essence of the material world is often revealed only through its inevitably broken nature. They propose to look at disconnection not as an exceptional condition, rather as the mean by which societies can learn and learn to re-produce, digging under the surface of appearance to understand causes and solutions of breakdown. (Thrift and Graham, 2007)

Figure 02

Nina Katchadourian, *Mended Spiderweb #19* (Laundry Line), 1998

If all the working things are alike, all the broken things are broken their own way: failure produces learning, adaptation and improvisation. Design should take on repair, in its widest meaning, as a way to act on the existing world, a process of improvement and learning, an empirical application of *broken world thinking*. Paradoxically, as opposed to the myth of novelty according to which innovations happens only thanks to flashy breakthroughs, the practice committed at repair might result in a solution-driven innovation, an experimental use of design's cut-and-try iterations to the concern of decay and erosion of our material world and its relationship with the environment.

> *«Design is a powerful analysis and repair tool. Encompassing all scales, applications and dimensions [..] and seeking for each goal at hand the best and most economical, ethical and elegant way to achieve it within the limits and with the materials available, it is one of the most consequential and constructive human enterprises.»*
> [Antonelli, P. (2019). *Broken Nature*. In: P. Antonelli and A. Tannit, *Broken Nature*. XXII Triennale di Milano, 1st ed. Milano: Electa, p.9]

Paola Antonelli, curator of the international *XXII Triennale di Milano* in 2019, entitled *Broken Nature: Design Takes on Human Survival*, asserts that design should spark the rebirth of this new innovation, a well-conceived strategy of reparation of the broken relation of man and planet earth. Design should make up for the destabilizing direction that human progress undertook in the last centuries, and its devastating impact on environmental decay. The international exhibition showcased innovative and provocative contributions of artists and designers from 21 countries, around the crucial issue of

Figure 03

Ponte Morandi, Genova (August 15, 2018)

The tragic collapse of this bridge in August 2018 is a tremendous warn of the importance of maintenance.

human survival in the age of the anthropocene. A considerable number of topics is addressed: the acknowledged reality of the climate change, the complex entanglement of relations of nature and man (considering the wide diversity of cultural mores), the global waste crisis, the conservation of the biosphere. The wide horizon exposed to the visitors portrays the complex, yet inestimable, diversity of challenges that design is called to advocate: the scope is not to showcase a number of sheen innovations and catchy solutions, rather to direct the public's attention to critical points, to ongoing conflicts of man and of different cultures with the environment. For, if modern design is a human centred, problem solving practice, a proud servant of the Industrial Revolution whose devotion towards human survival can only be perceived through the subjugation of nature, design should take on a key role in the transfer of scientific knowledge into culture and behaviours. Design is a crucial medium for surveying humanity's bonds at survival, for the recognition and communication of the broken nature of our present and the tool of choice for the definition of strategies of maintenance. Its goal will be, in this light, the design of strategies for the reparation of this broken reality made of objects, buildings, physical and ephemeral infrastructures. (Antonelli and Tannit, 2009)

Restorative and Regenerative Design

Many interrelated innovative design thinking concepts are challenging the traditional way of conceiving constructions: the design used to be led through to meet some final needs, in terms of function, comfort and budget. Sustainable architecture of the early environmentalism added few to this concept but the energetic impact and the evaluation of buildings' footprint. Though it will be more and more necessary to think of buildings more as of dynamic and interactive structures. (Nugent et al., 2016) These all are the premises of a paradigm shift towards restorative and regenerative design: more than brand new technical means for designers, they devise a renewed interest and understanding of the built environment. To make sustainable development become a reality, a "do less" approach will not be prosecutable any longer: the built environment needs to become part of climate regenerative solutions. Restorative design depicts a practice capable of healing social and ecological systems to a healthy state: it is an extension of the conservation capabilities of those corrupted infrastructures, those bonds in danger of decay. As restoration, it inherits an old, layered world: though aiming for the durability of the old, it pursues also the appearance of the new. (Jackson, 2013)

Just as much as restaurants are places where one's health and temper can be restored without compromising pleasure and wealth, regenerative design aims to empower its objects to easier preserve their healthy state and to allow their eventual evolution. Restorative or regenerative design are new paradigms of design thinking and practice: they refer to new concepts such as *living* or *adaptive buildings*, forming a new vocabulary that will probably be different from that of sustainability and environmentalism. Albeit not completely developed and precisely defined, they all seek to integrate and repair the natural and artificial environment in a holistic and systemic manner, rather than addressing building design itself, aiming for buildings that not only sustain their needs on-site, yet also able to participate to the cycle of nature, in order to allow change and innovation, at best being able to participate to the environment. (Brown and Haselsteiner, 2018) The growing conscience of the mutual and complex interconnection of the artificial with the natural environment urgently calls for design methodologies that, starting from the reality of facts, allow for a reconnection of technology and culture to nature and the ecosystems. (Oxman, 2016) It is by no means to forget that this change will happen accompanied by an inevitable transformation of social and economic structures towards a new model of circular development, different from that of seamless production, progress and mere growth. This can not be pursued by means of creating of a brand new world, since earth bonds impose us some ineluctable borders: rather it will be possible by means of a careful commitment and care at repairing our own broken present.

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01.2 ADAPTIVE BUILDINGS

Environment based definition of adaptivity

A changing climate, a shifted mentality towards nature implies a renewed ability of the built environment to adapt to the environmental conditions that will affect our cities within the next few decades. For, if sustainability and the paradigm shift of a broken world to repair is also a matter of cultural and collective perception, its vocabulary assumes a substantial relevance. The jargon of climate science and sustainability, of biology and engineering, is more and more shaping the discourse on the built environment, its definitions being used by consultants, scientists, ecologists and policy makers all over the world, not rarely without any confusion and misuse. The field from which most of the influence comes is primarily climate change science, around the phrase *Climate Change Adaptation*. (Brown and Haselsteiner, 2018) However, to avoid many frequent misreadings of the concept of adaptation and its contextualisation, it is worth to consider what this term actually means to its prime field of use: before of being adopted by climate science researchers, the words *adaptation* and *adaptivity* used to be the bread and butter of evolutionary biologists.

> *«The significance of an adaptation can only be understood in relation to the total biology of the species.»*
> [Huxley, J. (1942). *Evolution: The Modern Synthesis*. 1st ed. London: George Allen & Unwin, p.449]

In evolutionary biology, adaptation defines a continuous dynamic process, rather than a physical form or a feature of an organism. Its role and significance, in correlation to evolution, can't be defined *per se*, though it needs to be referred to the whole of an ecosystem. (Mayr, 1982) Any adaptation process leads the organism who undertakes it closer to fitness in its specific environmental context. There are three possible definitions of adaptation, as classified by the biologist Theodosius Dobzhansky (1900-1975): *adaptation* is the evolutionary process described above, *adaptedness* is the degree of adaptation reached by an organism, his ability to overcome difficulties of his particular habitat. Lastly, an *adaptive trait*, in other words a phenotypic trait with a functional role for the organism's fitness which enables the evolution, whereby enhancing the chances at survival to natural selection. ("Adaptation", 2019) As the domain of *adaptation* (and its relatives) shifts from biology and genetics to climate science, the focus shifts on human survival. For, if we recognise that the built environment accounts a major responsibility for climate change and for human imprint on the planet, it will be more and more important to talk about adaptivity also in

Figure 01
Liam Young, *Tomorrow's Thoughts Today* (2017)
Part of Young's dystopian Under Tomorrows Sky.

architecture. The problem emerges when we realise that our settlements on this planet not only are very few sustainable, but also that the imprint they have already left on our planet is probably irreversible. This is the moment in which *adaptivity* substitutes *sustainability* as a main paradigm.

Among the greatest of all misstatements, often kept going in daily life and contemporary design practice, is that of a possible globalisation of climate adaptation. In her essay *Air Conditioning: Taming the Climate as a dream of Civilization*, the German cultural studies scholar Eva Horn warns us about the role that state of the art air conditioning, that has gradually become a mainstream cultural trend, based on human centred comfort design for climate adaptation. A real standardization of interior climates worldwide, by means of an infinite repetition of the identical heating-cooling routine everywhere, regardless of the different weather and atmospheric conditions. Few doubts, it is a fulfilment of the long-term dream to relieve the human societies from the contingencies of nature, of the primal need of man for insulation, what Peter Sloterdijk, German philosopher, addresses to as protective *Sphären* (spheres). Air conditioning is not only an admirable technical innovation but a crucial element in the project of civilization: one that, raised in less than one century from the need for air treatment in the huge industrial plants, allowed the economic ascent of cities such as Singapore (the *Air-Conditioning Nation*) where the sweltering tropical heat used to be a serious bond to the development of a western-like financial economy. Half of the energy consumption in Singapore is indeed spent by cooling systems, allowing an office building in South East Asia to achieve the same level of temperature as one in Toronto, New York or London. Little wonder that built environment's operational energy accounts for a large part of world's CO_2 annual emissions: as we spend more and more time in indoor spaces, the final irony is that we will become less and less able to withstand the outer climate, both because of Global Warming and because of a radical loss of *climate intelligence*. (Horn, 2016)

«Ultimately, the venture of controlling and dominating nature comes into its own in the dreams of creating an atmosphere that is completely adapted to human needs and comfort.»

[Horn, E. (2016). *Air Conditioning: Taming the Climate as a Dream of Civilization*]

This paradigm exemplifies the broken relation between climate and culture, nature and technology, environment and humanity. It is in fact overturned: does adaptation mean that we should design our artificial sphere of protection, regardless of its backlash? Adaptation is by no means to be seen as a generic concept: on the other hand, it firmly reminds the importance of the relation with the specific environment and ecosystem.

Risk based definition of environment

The key element of adaptation is, inevitably, the environment, in which this process happens. A definition of the environment today can't really do much without the observation of the effects of man on nature, therefore of the reality of climate change: the branch of science devoted to assess the entity of the ongoing climate transformation is a field known as *environmental statistics*. Its growing relevance, although the relative novelty of this field, is allegedly connected with the increasing environmental degradation and the need by governments and policy makers of precise data and projections regarding this process. The scope of this field of scientific research is wide, covering in fact both the biophysical side and the socio-economic aspects that dynamically interact with the environment. (United Nations, 2017) Decisional power today can hardly neglect the implications of environmental risk in modern societies. Ulrich Beck, German sociologist, describes the contemporary society as a *risk society*: one in which it is the distribution of risk, rather than that of resources, to matter the most, a society that is systematically geared towards hazard and uncertainties. (Beck, 1986)

A *risk society* is by no means one that is more dangerous: while in past social orders the *risk factor* was taken as granted, as a faith imposed by gods, what is relevant is the epochal (and, most probably, irreversible) advent of the *manufactured risk* over the *external risk*. The closed relation between decision and risk management renewed the importance of responsibility in modern societies. The concern about risks in contemporary strategies and decision making is the main feature of the *reflexive modernization*, in which the fulfilment of the desired degree of safety is pursued by means of increased regulations, to eventually anticipate any possible scenario. It is in this context that the idea of *sustainability* blossomed, as well as the concept of the *precautionary principle*, or the social responsibility for protection of the community from exposure to harm and danger, usually in contexts where the evaluation of risks implies a high degree of uncertainty. (Giddens, 1999) Disasters are one of these occasions, right away from this word's origins: from the Greek prefix *dus* (meaning "bad") and *aster*, stars, the idea of calamities as a faith imposed by nature is deeply rooted in our

Figure 02

Amatrice (2016)

Post-apocalyptic scenario, consequence of the strong 24th August event. Many buildings fell, causing about 300 casualties and thousands of displacements. Some buildings, though, resisted, such as the bell tower.

culture. (Davis, 2018) But is this still an acceptable representation of an environmental disaster?

It is, indeed, the man's hubris or carelessness to provoke some of these events and the casualties they lead to. On 25 April 2015 a disastrous earthquake hit the Gorkha District at Barpak, Nepal. With a magnitude of 7.8 M_w (or 8.1 M_s), these seismic events, on one side, surely demonstrated the astonishing destructive power of nature. Though architect Robin Cross argues: earthquakes don't kill people, buildings do. Three fourths of the fatalities were in fact due to buildings' failures: the tragic death of more than 8500 people, not to mention the tremendous amount of nearly 3.5 millions of people left homeless, makes of the Gorkha 2015 quake one of the most disastrous in history, although its occurrence at 11:56 was probably a life-saving coincidence for most of people that was outside of home at that time of the day. Human responsibility owns an important role in this dramatic play: seismic events of this relevance are by no means new to Nepal, the last of them occurred in fact in 1934, nor there is an evident lack of knowledge. This disaster was sufficiently predictable, though the lack of resources and care was the most relevant risk factor. Earthquakes are in fact not simply "natural crises", they reflect an ongoing crisis of urban development, where the most informal suburbs, aftermath of the rush-hour of out of control urbanization, own invariably the higher degree of exposure. (Cross, 2015) It is not admissible to ignore that large scale natural disasters are primarily linked with social and individual responsibility and with collective memory, nor to look past the physical characteristics and intrinsic risks of a site in the name of an unquestioned innovation. (Tannir, 2019)

Italy has a rather medium-high degree of seismicity: it is, in other words, easily expectable that, in a short amount of time, a quake of considerable magnitude will occur somewhere on its territory. Given this consideration, Italy can boast an adequate wealth of knowledge in terms of seismology. Yet, many recent events showcased the high degree of weakness and exposure of many regions. The Central Italy Earthquake, a long sequence of tremors between August 2016 and January 2017, is the most severe earthquake swarm of the last three decades. Tremors started on 24 August, at half past three in the night. The 6.2 Moment Magnitude quake, with its epicentre near the town of Accumoli, in the Lazio region, caused the death of 299 people and over 2000 forced displacements. But the nightmare for central Italy was not over: in the following weeks and months a series of aftershocks cursed a wide area between the regions of Lazio, Abruzzo, Marche and Umbria. On 26 October tremors increased considerably their magnitude, reaching their climax on 30 October: the 6.6 M_w quake, with epicentre between the towns Norcia and Preci is the strongest recorded in Italy since the 1980 Irpinia earthquake. The second acute swarm displayed another terrible consequence of earthquakes: the irreversible damage to the historical and artistic heritage of towns such as Arquata del Tronto, almost completely destroyed, and Norcia itself, where the disruption of the Basilica of San Bendetto became the tremendous mark of this tragedy. A final severe swarm hit these regions again in January, reaching a magnitude of 5.5 M_w. This last event became sadly famous for the tragedy of the Hotel Rigopiano: a facility on the flanks of the *Gran Sasso* got hit by an earthquake-triggered avalanche. (Protezionecivile.gov, 2017)

R*isk mitigation* strategies

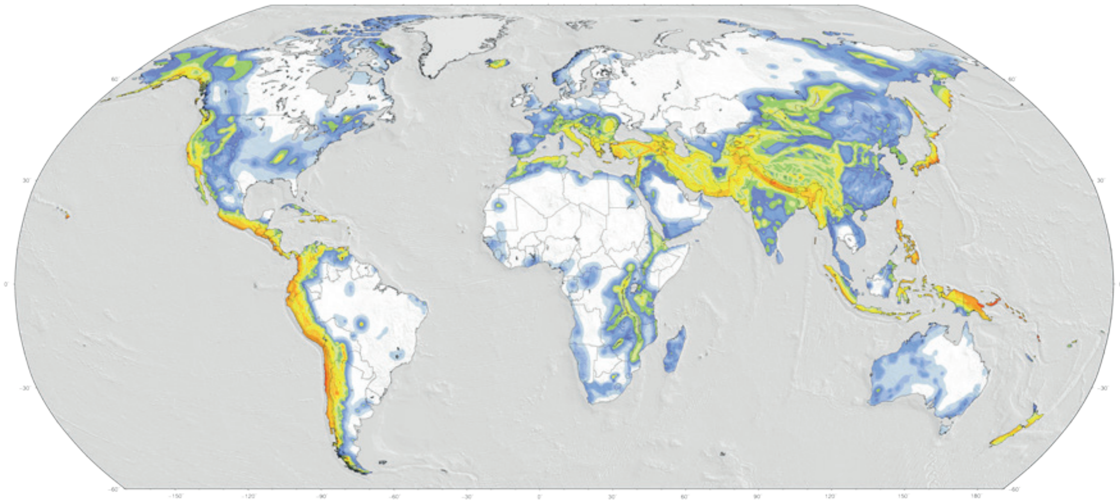
The long *Amatrice*, *Norma*, *Vissio* sequence of seismic events reminds us of the complex entanglement that human responsibility establish with nature and its catastrophes. The complex long-term operations of recovery and reconstruction, as well as the high costs for public funds, (Tortora, 2019) demonstrates the importance of resilience. A definition of seismic risk does not only imply *seismic hazard*: since it measures the damage expected in a given time frame with a certain probability, it has to account also for the resistance of buildings and for the nature, quality and quantity of assets exposed in a particular region. (Protezionecivile.gov, 2019) Hence, even if the *seismicity* is not as high as in many other countries (Japan, Indonesia or the western coast of continental America), the high *vulnerability* of the building and infrastructure's asset and the extremely high *exposure*, consequence of a one-of-a-kind anthropisation and density of historical, artistic and monumental heritage, make of Italy one of the first countries by seismic risk. (Globalquakemodel.org, 2018) An adequate risk management program can consistently reduce vulnerability and exposure, therefore retain social, economic and physical losses that are usually caused by such catastrophes. Risk reduction plans might include emergency response

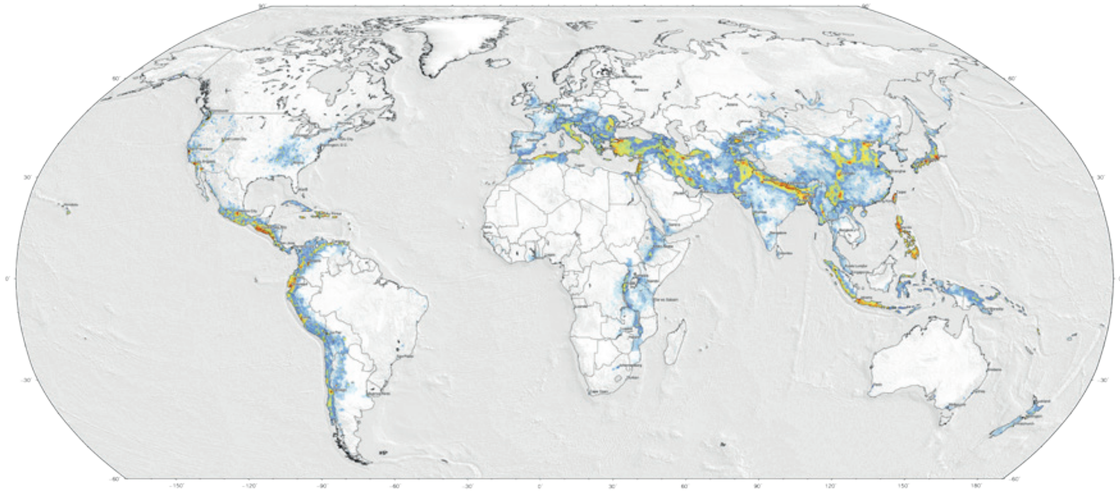
Figure 03
(Next page)

Seismic hazard and risk planispheres (2018)

Above: global seismic hazard map showing the Peak Ground Acceleration (PGA) in units of g (gravity) with a 10% of exceeding probability in 50 years

Below: global seismic risk map, portraying the distribution of Average Annual Losses (by construction costs, USD/m²), seismic hazard, exposure and fatalities maps.





strategies, the development of insurance pools, the enforcement of design codes and the creation of retrofitting campaigns. (UNISDR, 2017)

However, the adoption of similar strategies in Italy happened all too often as a consequence of the most destructive seismic events of the recent national history, reducing their ability to actively prevent the repetition of such disasters and consequent losses. (Dolce, 2012) The definition of emergency plans is since 2012 task of the municipalities,[01] although the coordination of these plans, as well as that of operations in case of emergencies, is duty of the *Dipartimento della Protezione Civile*, the national body for prediction, prevention and management of exceptional events. These plans include a picture of the territory's structural features and weaknesses, establish the goals related and specify fields of operation and responsibilities of the operators in cases of emergency. Contrariwise, the stipulation of insurance policies does not fall within the duties of public administration, nor of private homeowners. The absence of such measures causes all of the costs

[01] L. 12 luglio 2012, n. 100, in materia di "*Disposizioni urgenti per il riordino della Protezione Civile*"

of these catastrophes to be borne by the public sector instead of being, at least in part, supported by the private insurance market. While a proposal for a law in this regard was advanced in middle 2012[02] (irony of destiny, just a few days before the 2012 Northern Italy earthquakes), the final approval of these measures didn't make it in the final draft, mostly because of the political circumstances. Although the diffusion of private policies is low (in comparison to other European countries such as France, where since 1982 any insurance contract also comprises natural disasters, or Spain, where the responsibility is state owned) **(Gaita, 2016)** it is expected an increase at a annual rate of 20%, thanks also to the introduction, since 2018,[03] of a significant tax deduction connected to their price. **(Casaeclima.com, 2017)** However, since the insurance costs are related to the the vulnerability of the building being secured, the duty to secure an asset could ignite a serious retrofit campaign, involving both public and private owners. **(Franco, 2016)**

Resilience and adaptation

The issue of an anthropic responsibility towards earthquake losses is an old concern: the earthquake is part of the culture of those populations that have undergone it, and every epoch dealt with this natural phenomenon expressing different cultures of resistance and resilience, though sometimes the consideration of technologies of construction is restrictive, if compared to the entire cultural phenomenon around these natural disasters. However, if we admit the difference in the contemporary approach to the vulnerability of constructions with that of past centuries, this difference is to be found in the scientific and methodological approach that followed the deeper understanding of geology developed in the late XIV century. Before of this "scientific revolution", that led the design for seismic actions to become a very specific practice, with the strong knowledge and performance based methodologies proposed by today's standards, seismic design used to be guided by the experience that was gradually built over the centuries. By no means these considerations imply that the tradition-led method proofed unable to produce a safe built environment; on the other hand, this underlines the historic and cultural importance of the topic of risk and of resilience along the course of history. **(Laner and Barbisan, 1986)** Pirro Ligorio (1512-1583), is invited by the *House of Este* to observe the consequences of a strong earthquake in the area of Ferrara in 1570: this event sparks a great interest in the Neapolitan architect, who even dedicated a treatise to this topic, convinced that to build safe constructions was a duty of human intellect. In the last chapter, he proposed the plans for an earthquake-resistant home, based on the long southern Italian tradition of wooden reinforcement frameworks absorbed within the masonry walls, that allowed many buildings to resist until today. **(Cantelmi, 2017)** This technique, well known in many other cultures, eventually became part of one of the first acknowledged seismic design codes in history in March 1784, the instructions for the reconstruction of Reggio Calabria. **(ISI, 2019)**

[02] D.L. 15 maggio 2012, n.59, in materia di "*Disposizioni urgenti per il riordino della Protezione Civile*"

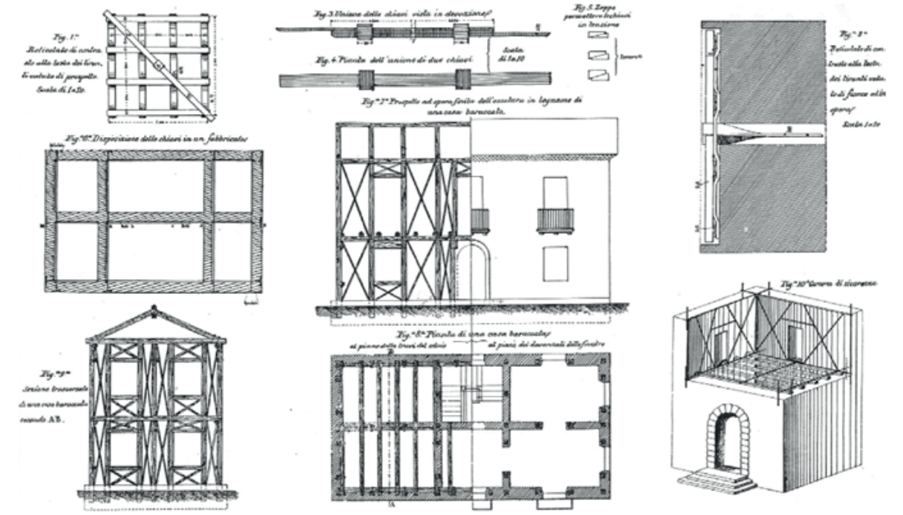
[03] L. 27 Dicembre 2017, n. 205, in materia di "*Bilancio di previsione dello Stato per l'anno finanziario 2018 e bilancio pluriennale per il triennio 2018-2020*"
Measures and bonuses confirmed also in the: L. 30 dicembre 2018, n. 145, in materia di "*Bilancio di previsione dello Stato per l'anno finanziario 2019 e bilancio pluriennale per il triennio 2019-2021*"

Figure 04

Luigi Pesso, *Sistemi di prevenzione sismica: tiranti in ferro, casa baraccata e camera di sicurezza* (1876)

A set of design solution for a seismic proof house of the late XIX century, with wooden and iron framework immersed in the masonry perimeter walls.

A traditional technique, known and diffused in southern Italy.



[04] D.M. 17 gennaio 2018, in materia di "*Aggiornamento delle «Norme tecniche per le costruzioni»*"

Structural design codes have been enforced ever since, along with the innovation of state of the art techniques of construction: following the *precautionary principle*, the evolution of seismic codes specify the ever growing standards that civil structures must achieve to ensure safety, considering the seismic hazard specific of their region. They are the underhand work of a "culture of earthquakes": contemporary codes arose from the adaptation of former ones and are firmly based on a rich historical database of seismic events. The Italian catalogue, drafted by the *National Institute of Geophysics and Volcanology* (*INGV*), provides homogeneous macro-seismic and instrumental data and parameters for the over 4500 earthquakes, with maximum magnitude bigger than 4.0, in a time frame between 1000-2015. **(Rovida et al., 2016)** The *response spectra*, used in contemporary seismic codes, are in fact probabilistically determined according to these historical records of *peak ground accelerations* (*PGA*): they define a maximum structural response in terms of acceleration and displacement, depending on the structural properties (mainly the *natural period of vibration* T) and adjustments based on the site's geophysical characteristics. The reference *PGAs* are chosen for each zone of seismicity, corresponding to a reference *return period* T_{NCR}, that is the expected return time frame of the reference design earthquake, or, connected to it, to the *probability of exceeding* P_{NCR} (in other words the "cut off" percentage of likelihood of an event with specific parameters to happen in a defined time frame). The choice of different T_{NCR} and P_{NCR} ties in with the selection of a proper level of security requirements, four according to the Italian code.[04] Although the use of acceleration spectra gathered from an history of seismic events is admitted, there is by no means the certainty that a future earthquake will manifest with a similar acceleration spectrum. This process would imply to envelope of many different histories of seismic *PGA*: known the displacements, the stresses are proportional to the stiffness of the structure. A probabilistic determination of seismic actions, such as that of *response spectra*, is desirable. **(Cimellaro and Marasco, 2018)**

Though, in some cases, the enforcement of building codes is not enough, since it doesn't guarantee the compliance of old buildings to the renewed standards: when the *Great Hanshin* 6.9 M_w momentous quake stroked the city of Kobe (Japan) it appeared, crystal clear, that, for the most part, the 150.000 building destroyed had been built before of 1981, year of the introduction of the new *Building Standard Law*, including a coefficient that varied with structural vibration period, and a two level design procedure. **(NIST, 1996)** Nor the evolution of codes and technique has been in some cases exempt from reprehensibly oversights, such was that tragically revealed by the consequences of the 1908 Messina earthquake:

> *«Dopo il terremoto che nel 1783 devastò le Calabrie, il Governo borbonico emanò il 20 marzo 1784 dei provvedimenti che [..] appaiono informati ad una grande saggezza ed è veramente a deplorare che, nel giro di pochi lustri, essi siansi lasciati cadere nell'oblio, [..] sapendosi di case che, costrutte sotto l'impero di queste prescrizioni, resistettero a tutti i terremoti successivi [..]»*
>
> [Maganzini, I. et al. (1909). *Relazione della commissione incaricata di studiare e proporre norme edilizie obbligatorie per i comuni colpiti dal terremoto del 28 dicembre 1908 e da altri anteriori.* Giornale del Genio Civile. Roma: Stabilimento Tipo-litografico del Genio Civile]

The importance of the cultural representation and attachment to the history of natural catastrophes is a call to action. The catastrophe of Messina, among the most tragic of the XX century in Italy and in Europe, is a turning point for the diffusion of reinforced concrete. Although at times the history of this new material is still at its beginning, reinforced concrete frames are cheaper and lighter, yet durable and flexible: they become the protagonist in the post-disaster debate on reconstruction. The intense tectonic activity of the peninsula considerably affected the development and wide diffusion of concrete all along the past century. **(Iori, 2009)**

Crucial, on the path of a consistent risk mitigation, is the topic of urban resilience. **(D'Amico and Currà, 2014)** The meaning of *resilience* is tied symbiotically with that of *adaptation*: adaptivity improves resilience and, indeed, a resilient structure is one that is best adapted to the risk of its environment. A functional definition of resilience measures the ability of a system to reduce the chances of a collapse and the amount of time needed after a shock to restore its full performances. A resilient system is one that is capable of reducing the chance of failures, while also limiting the consequences and the time to recover up to the normal level of functionality.

[Community Earthquake Loss of Resilience] $R_L = \int [100\%-Q(t)]dt$

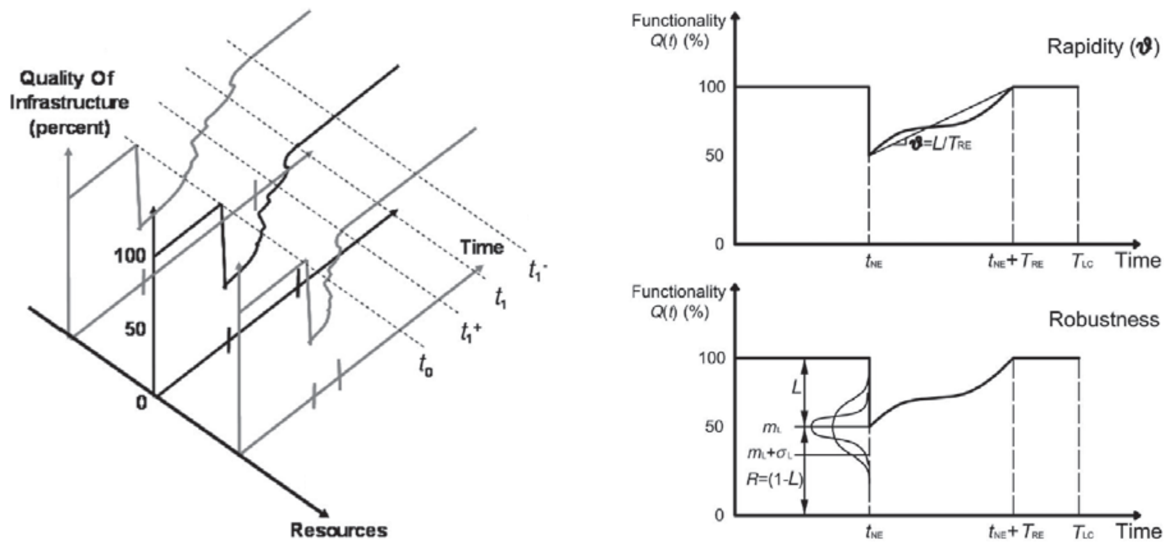
The proposed definition of resilience has the inherent merit to frame the problem in a wider social context that can be generalised to different structures, assets and communities. **(Bruneau et. al, 2003)** Different levels of functionality are possible at the same point in time, varying according to the availability of resources implied for the construction and repair of the infrastructures. The definition of the degree of resilience can't do without a stochastic definition of the degree of risk of a territory, as it has

Figure 05
(Next page)

Resilience graphs as function of time (2008)

Left: expansion of resilience in the resourcefulness dimension.

Right: rapidity and robustness as dimensions of resilience.



been explained above in the definition of seismic safety levels: different curves with different degrees of functionality at the same point in time represent structures designed considering different degrees of threat. Resilience consists of four properties: rapidity, robustness, redundancy and resourcefulness. Rapidity represents the slope of a functionality curve, and it can be determined in averange for a given amount of total losses and the total time needed to recover the initial state. Robustness, instead, accounts the residual functionalities of an asset after the extreme event: it exemplifies the strength, ability to withstand a given amount of stress without experiencing considerable functional losses. Finally, redundancy defines the ability of a system to satisfy alternative functional requirements in case of extreme conditions, and resourcefulness is the ability of a community to put at work external resources (i.e. financial or productive) along the process of recovery. These latter properties can influence the first two mathematical properties of the functionality curves. **(Cimellaro et al., 2008)** The popularity of this term has increased consistently in many fields of interest, to a point in which it must be regarded as a *buzzword* for the next century, just as much as sustainability is. In its most common meaning, resilience is therefore a mathematical function of the serviceability of an asset over time, namely the quality of its functions expressed as a percentage, though some other literature stress the affinities with the ability of individuals or communities to adapt to changes and demands occurred as a result of a catastrophic event. **(Gallopin, 2006)** The process of adaptation, in this light, differs from the canonical definition of resilience: a system would not, eventually, simply bounce back to its pre-disaster state, rather to a different, more adapted one, evolved in relation to the altered circumstances. For, if a resilient community can exist outside the boundaries of sustainability, a sustainable community can hardly do without holding at least some degree of resilience: natural events will change the way we live, hence resilience will contribute to a sustainable development. **(Saunders and Becker, 2015)**

Sensitivity and redundancy

Change is an inevitable condition of the environment: the less the friction at change of buildings, the better the degree of adaptation achieved will be. Two of the qualities that can guarantee a long-term efficiency of natural and artificial systems are *sensitivity* and *redundancy*. The former is employed for instance by many living beings to adapt to outer changes is by actively interacting with them: they deploy sophisticated sensor systems and, following an external stimulus, adaptive response strategies, embedded between the material and structural level of their body. (John et al., 2005)

The *Strandbeesten*, made by Theo Jansen, are not just amazing engineered kinetic machines, rather artificial living beings, able to live by themselves and to evolve adapting constantly to their environment. Just as much as nature creates life, they are made of a simple set of materials, and their evolution is based on their ability to use energy efficiently and economically, and to resist the severe changes of ground and atmospheric conditions. They even show amazing abilities of *homeostasis*,[05] using basic passive sensors and devices designed by Jansen himself. (Strandbeest.com, 2019) Structures are designed nowadays according to loads defined stochastically, taking into consideration a design life parameter and extreme conditions. Meaningful advantages in terms of whole-life energy savings have been recently investigated in the *Adaptive Structures* exhibition at *The Building Centre* (London, 2016). A dramatic reduction of embodied energy in the structural elements might be reduced with the design of active components and the careful definition of their activation threshold (the specified level of stress or deformation, above which the actuators become operational). A passive structure is, in other words, an active structure with an activation threshold set to 100% (inactive in any possible condition), a structure that does not require any energy to operate, but that embodies far more energy by design. Active structures might be able to respond to heavier loads by means of sensors, control intelligence and actuators. Key is to define the right balance between passive and active behaviours, to minimise the amount of operational energy. (Senatore et al., 2011) These two examples, seemingly very distant, share a common worthiness, since they both address to a consistent problem of adaptation intended as a dynamic process: a dynamic equilibrium requires adaptive-traits.

[05] The ability of living organisms to reconfigure their state of equilibrium in response to external change.

A whole building approach

The word *Homeostasis* devises a dynamic equilibrium, the fragile balance of energy and material flows that allow living organisms to withstand changes of the ecosystem. Some species, though, are known to adapt to their environment by building structures that facilitate, for instance, the process of thermoregulation of bodies. Termites, among the most successful groups of insects on Earth, are also unexpected great builders. They live in huge colonies, based around these insect's main activity, the drawing and storage

Figure 06

Theo Jansen, *Strandbeest* (2018)

The skeleton-like, plastic-made kinetic structures of the Dutch artist show how, by taking on the concepts of adaptation and evolution, artefacts can bring the relation with nature to much further extents.

of cellulose out of wood or grass, hosted in these self built mounds. In some of these colonies, termites live symbiotically with fungi, receiving food, water and protection in exchange for the digestion of cellulose: a temperature of about 30^0 C has to be maintained in order to allow survival and growth. However, it is not because of their dimensions, but because of their unique organisation that these moulds have been studied by evolutionists: their inner channel and porous structure provides constant ventilation, humidity and carbon dioxide concentration, opposing to both termites' self heating and environmental outer conditions. (Richards, 2019) Although species colonizing different areas of the planet share very common structures, subtle differences occur to allow the integration of the colony in that specific atmospheric context. (Korb, 2003)

Many animals build their homes to preserve a delicate equilibrium against the fluctuations of the environment, still being able to exchange energy and matter with the ecosystem, using natural cycles at their own advantage. To draw the physiological boundary at the skin of such creatures is, as J. Scott Turner points out, an arbitrary operation: termite mounds are *extended organisms*, integral part of the adaptation strategy. (Turner, 2002) Adaptation does not depend solely on the efficiency of a set of components, rather on that of the overall system and its relationship with the environment: it is often the inefficiency of one part, in natural ecosystems, to make the whole system efficient. The growth of a tree, for instance, is not merely single-purpose: it provides food for animals, insects, micro organisms and it

enriches the ecosystem, seizing carbon, producing oxygen, cleaning air and water, creating and stabilizing the soil around them with their organic waste. (McDonough and Braungart, 2002) The ultimate challenge of adaptation lies in a holistic, organic understanding of buildings as *extended organisms*.

Figure 07

Nasutitermes Triodiae's mounds.

It can take up to 5 years to build one of these natural "cathedrals", and it can reach 8 meters in height.

A whole building design conception is necessary to guarantee the long term efficacy of the energy performance of a building as a whole, including that of multi-storey, large scale buildings, well known to account most of the energy consumption of the built environment, and constituting therefore a pivotal challenge. The building envelope is what, more than any other functional components, controls energy consumption and exchange of matter and information between the inside and the outside: no longer to be seen as a static component, rather as a layered, dynamic system, intelligently responding to the impulses coming from the environment. (Shahin, 2018) The employment of climate responsive features finds in today's practice widespread application, made possible by the innovation and enhancement in automation, materials, sensors and actuators, design for manufacturing and digital fabrication. (Loonen et al., 2013) However, the achievement of adaptation is not simply to be pursued by adding adaptive items: multiple, dependant and often at odds environmental requirements must be satisfied. Natural light, thermodynamic balance, air handling and natural ventilation are some of the design criteria that must be considered organically.

Figure 08

Piazza del Campo, Siena

The *Palazzo Pubblico* in Siena, built at the beginning of the XIV century, experienced heavy modifications all over his history, constantly evolving with the evolution of society inside and around it: once host of the ancient Republic's seat, a role conserved till nowadays as host of the city's administrative court.

Adaptive buildings

To understand the importance of adaptivity in the built environment, we should perhaps start seeing our buildings as living things. Stewart Brand, American writer, is fascinated by the way that buildings are at war with time and change: common to most buildings is that they always loose. Based in the city of San Francisco for around 40 years, he observed the city growth and ceaseless change, sometimes for the best, some others for the worst. To understand what makes certain buildings keep getting better over time, it is necessary to study what happens after buildings are built, when the user takes control. Some buildings are, by design, at war with change: most of times, he argues, because architects themselves didn't want their buildings to change. Though there is another road, that would allow the built environment to adjust to the common sense and everyday use. This used to be true, somehow, for buildings in the *Renaissance*, buildings that were designed not to be merely single purpose, when a certain degree of freedom was granted, for instance in the generous abundance of generic spaces, in the proneness of historical masonry architecture to be additively modified over time. On the other hand, with the advent of modernity, architects started to conceive their buildings as static and fixed objects, and the way buildings function, the way they are built, managed and maintained is often far from the attention of critique. (Brand, 1994) Every building is a prediction, every prediction is inevitably wrong: although this might seem a cynical disclaimer, the death of architectural design, this acknowledgement instead opens the possibility for architects to assume a different role:

> *«[..] stop defining time and put time to work. Evolutionary design is healthier than visionary design. Contemporary buildings can learn about time, flexibility and evolution from models like Siena.»*
>
> [How Buildings learn (1997) [TV series] Directed by S. Brand and J. Muncie. London BBC]

Organically grown towns and cities are the most durable and valuable; the rationalist predictive urban planning practice is a failure: control, separation, zoning. They forecast a different perspective of the buildings and cities, designed so that they would be allowed to change over time, provided by design with a proper degree of flexibility and adaptability. The design of the new should put into account early modifications as well as long term repair and maintenance, just as much as the action on existing buildings should promote an increased level of adaptation of buildings to their environment and uses. To do so, architects and designers should consider time, in first place, as a decisive part of their equation, and think of buildings putting into serious account their useful life, questioning durability and evolution as the main drivers of their choices.

The popularity of the term *adaptivity* in the architectural discourse corresponds to a strong will to make buildings "future proof", or risk proof in *risk societies*. *Adaptability*, so often sought, so frequently misunderstood, has a long history: for a designer wanting to make his building adaptive, there exist a "black box" of adaptability, containing the solutions that, over the course of history, allowed buildings to survive the challenge of time, to change with their users, accommodating the ever changing conditions of societies and of the environment. Different strands of designing for adaptability are at-hand: spatial adaptation in first place, often pursued by means of spatial redundancy (the *loose fit*, or *form accommodates function*), flexible open plan design theories and the idea of an "unfinished" design, provided with a certain degree of ambiguity not to be caught off guard by future transformations. Industrialized architecture, whereby movable "bits" for movable buildings, open components as for kinetic architecture, promised abilities to reconfigure the plan to accommodate spatial, functional and climatic change. Urban theories, such as that of the *Metabolism*, attempted to develop a new model of cities' transformation based on the concepts of prefabrication, modularity, circular growth and urban renewal, still being devoted to the tradition of the Japanese housing, where the ephemeral nature of spaces enabled the construction of buildings that could be easily changed by deploying lightweight materials and precarious conditions. (Schmidt and Austin, 2016) Adaptation, in the context of climate change, is the process of adjustments in ecological, social and economic systems, (whereby renewed processes, practices and structures) rather than a "technological fix", but adjusted to its context, firmly declining the "one-size-fits-all" method. (Unfccc.int, 2019) Although different approaches can claim for many successful strategies at change, it is to expect that adaptability, in the future, will be perceived with models more and more away from those of a stereotyped idea of adaptation, mainly because construction and design for adaptability means in first place to question the state-of-the-art conventions, to challenge corroborated traditions. In first place reuse and recycle, as a way to improve and establish adaptability in the built environment, and as a process of adaptation themselves:

«Adaptability can be viewed as a means to decrease the amount of new construction (reduce), (re) activate underused or vacant building stock (reuse) and enhance disassembly/deconstruction of components (reuse, recycle), prolonging the useful life of buildings.»

[Schmidt, R. and Austin, S. (2016). *Adaptable Architecture*. 1st ed. New York: Routledge, p.6]

All buildings are adaptable, only they are adaptable at different levels: yet the degree of adaptation can be improved by reducing the energy and resources that a building implies while adapting to external transformation and pursuing this objective by minimising the frictions at transformation. (Schmidt and Austin, 2016) Design can take on the topic of adaptation by means of a commitment towards the circularity of processes and towards the topic of reuse and recycling, together with a deeper understanding of the environment, consequentially being a tool for the adaptation of the built environment. The definition of adaptation cannot help but reconfigure our very notion of buildings, as dynamic systems rather than static and inanimate instances: contextually, the layers of change and their related life-cycle must become a central topic in the design for adaptation. The responsibility and commitment of man at human survival and adaptation must be able to find consistency in new cultural and political trends. This can be perceived only at a systematic level, as systematic and complex is the degree of entanglement of technology, culture and nature: an adaptive methodological approach is intended to design holistically the adaptation of the existing building environment, while first understanding in depth its environment, layers and capabilities of transformation.

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01.3 A GREEN NEW DEAL

The environmentalisation of policies

For a long time, and with particular regard to the XX century, the influence of the building sector on the environment has been largely underestimated. The intense process of anthropization of the second half of the past century led to an urban development process lacking of adequate attention to their environmental quality. The outcomes of this issue are now for all to see and their backslash are not solely a matter of concern for specialists and professionals involved in the AEC field. The environmentalisation of culture and knowledge (firmly based on the modern scientific understanding of the environment of the complex relations with technology and of the centrality of the issue of adaptation and maintenance) is now part of a renewed collective critical consciousness about the role of the environment for human societies and the economy. These changed conditions demand for a profound change in the processes and activities of the building sector, with regard to the new expectations about sustainability. **(Gaspari, 2012)**

The evolution of policies is, in contemporary societies, the display of this gradual process of cultural, collective understanding of the entangled reality of mutual influence of man and the environment. Its relevance is wide enough, indeed being energy and resource provision everybody's business: little wonder that the evolution of policies towards environmental aware models is a difficult, slow process that hardly happens without any ambiguity and controversy. However, the strong motivations and commitment of the scientific community leave few doubts about the future of the planet: an action to limit the progress and effects of the global warming is necessary. The problem must be addressed at a supranational scale: since 1988, year of foundation of the *Intergovernmental Panel on Climate Change* of the United Nations. Its first document is published in 1992,[01] providing an international framework of action: the first treaty on the environment (based on the UNFCCC) dates back to 1997.[02] The *Kyoto protocol* would have become effective starting out from 2005, while in 2008 began the first commitment, reaching a total of 37 developed nations (members of the OECD,[03] most of which members of the EU), which pledged to reduce (by 2012) of a 5% in average their emissions (compared to the levels of 1990).The second period started in 2012 with the *Doha Amendments*: all of the EU-28 member states ratified the new version. These became effective in 2013, and so they remained until the beginning of 2020. The new objectives of the campaign have been approved in the COP 21 in Paris: finally, a binding agreement for all the 196 member countries. **(Minambiente.it, 2016)**

[01] United Nations Framework Convention on Climate Change (UNFCCC), Rio de Janeiro (Brazil, 1992)

[02] The *Kyoto Protocol*, Kyoto (Japan, Dec. 11th, 1997)

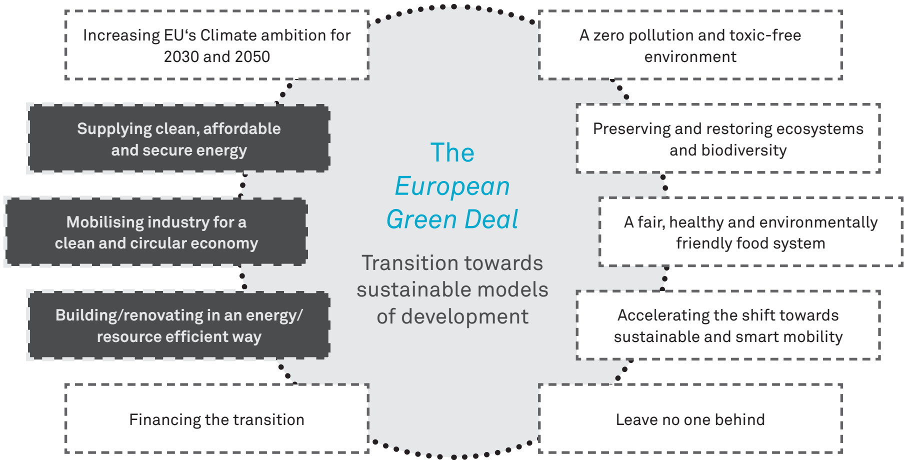
[03] Organisation for Economic Co-operation and Development (OECD)

International economic organisation, formed by 36 member countries, accounting for the vast majority of world's GDP.

Figure 01

The *European Green Deal* (2020)

Agenda for the future of EU sustainable development



The *United Nations Environmental Programme* (UNEP) annual reports, however, show unequivocally how the targets of the Kyoto protocol have hardly been achieved, meaning that the initial targets of emissions are now out of reach: even though the OECD members generally complied with the plagues signed (most often, however, by financing sustainability projects outside of their national territory), the astonishing pace of progress in developing countries led the overall increase of emissions. **(UNEP, 2019)** In Europe, the topic of energy efficiency makes its early appearance in the 1980s, when the petrol crisis forces the industrialised to question the provision and usage of energy as a crucial topic, also with regard to the economic and social equilibrium. From then on, the topic gained more and more importance, shaping the debate around the paradigm of sustainability. **(Gallo, 2006)** Today, the UN defines sustainable development around 17 goals, ranging between the social, economic and environmental compounds, as if complementary parts of the same problem. The transition to a sustainable model must happen without social nor economic injustice, nor with impacts on the planet. **(Sustainabledevelopment.un.org, 2020)**

For this to happen, a *Green New Deal* must be defined, promoting appropriate policies and their application at all the different levels, from the European to the national and regional ones. This process is not only intended to have a long-term impact on GHG emissions, rather also a positive impact on the employment and distribution of resources. The topic of an energy and resource transition towards sustainable development models is closely connected with the periodic financial market shortages and is indeed to be regarded as a measure of resilience against these physiological setbacks of world's economy. **(Schepelmann et al., 2009)** The idea behind the European plan for the next decades, defined as transitional towards a new model of growth prompted to sustainability of communities and economies, the ambitious promise of becoming, by 2050, a climate-neutral continent. To achieve this objective, the *European Green Deal* is thought to provide the boundary conditions (policies, investments) to empower research, investors and citizens to take part to the transition. **(European Commission, 2019)**

A sustainable urban development

In order to reach the key target of the 2050 strategy for the European Union (an economy with net-zero GHG emissions), a few intermediate goals and strategies have been agreed. The closer, at present times, is the plan for the next decade, willing for a reduction of at least 40% of GHG emissions by 2030. This objective must be pursued by means of two strategies: the growth of renewable energy share (up to, at least, the 32.5% of the total) and the improvement of energy efficiency (a reduction of the overall demand of at least the 32.5%, compared to 1990). **(European Commission, 2018a)** Cities and the built environment play a key role in the context of a transition towards a climate neutral economy. The building sector (meaning both the construction side and the life of buildings) accounts for the 40% of the overall energy consumption and the 36% of carbon dioxide emissions, being with distance the most energy demanding and pollution intensive field of economic development. **(Ec.europa.eu, 2020)** Doubling the energy efficiency of buildings would imply an overall reduction of 20% of the overall consumptions: indeed the 60% of the 2030 strategy's target.

Coming to the transition to buildings environmental sustainability, it is possible to define two complementary strategies: the strategy of efficiency (*a radical way of doing things better*) and the strategy of sufficiency (*a radical way of doing less*). The first is based on the assertion that the advance in technologies will allow in the future to achieve the same objectives with a consistent reduction of the energy requirement. **(Manzini and Vezzoli, 2008)** The introduction of the first *Energy Performance of Buildings Directive* (EPBD) was approved in 2002.[04] It is also the first EU level normative about energy efficiency of buildings: the member states are pledged to amend (within three years from the inception date) their national and regional regulations to the targets and measures set within the European directives. The 2002 EPDB defines the key performance requirements for new constructions and underlines at the same time the necessity of an improvement of the existing stock in case of actions of renewal, in so far of its technical, functional and economic feasibility. The most important novelty of this directive is the introduction of a mandatory *Energy Performance Certificate* (to be provided for new constructions or renovations, or when a unit is sold or rented out) in order to provide a unified means of comparison between buildings with regard to their environmental performance. The second version of the regulation of buildings' energy efficiency (the so-called *EPBD recast*) was approved in 2010, and is in force at present times.[05] This version introduced improved methodologies for the evaluation and definition by member states of cost-optimal minimum requirements of performance (in relation to savings in the entire lifecycle of buildings), as well as the new concept of *Nearly Zero-Energy Buildings* (NZEB), defined as high efficiency buildings whose minimum demand for energy is covered for the most part by the use of *Renewable Energy Sources* (RES), whether onsite or offsite.

[04] Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings (EPBD)

[05] Directive 2010/31/EC of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (EPBD recast)

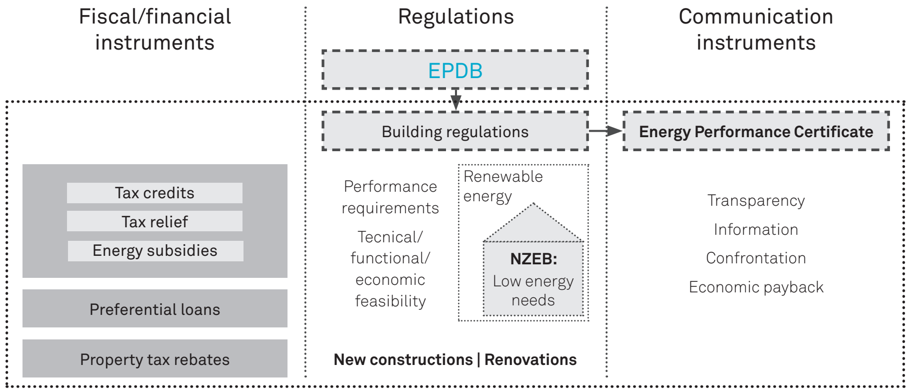
Partially amended in:

Directive EU 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency

Figure 02

The *EPDB* policy (2002-today)

Tripartite European strategy to improve the energy performance of the building stock, by providing improved regulations, fiscan and financial measures as well as communication instruments



The energy performance of buildings is connected with the crucial sector of energy provision. Policies regarding the built environment can, at the same time, contribute consistently to the planned improvement of the share of renewable sources, and in fact led most of the development of renewable technologies and markets. The member states are pledged to amend their national strategies to the key objectives and regulations defined by the EU in this regard: the first, in 2001, underlines the key role of this sector for the environmental and economic sustainable development of the European community.[06] The energy coming from RES is the active contribution of external sources, while the usage of passive strategies for the reduction of demands (although encouraged by the EPBD) are not regarded as such. The latest version has been approved in 2009, and is now in force.[07] The Italian EPBD and RES corresponding regulation is the *Minimum Requirements* law, in force since 2016, which defines the performance targets in terms of energy efficiency and use of renewable sources of energy.[08]

The preoccupation for energy efficiency, although being necessary, is not sufficient alone to guarantee the attainment to the ambitious goals of the *European Green Deal*. Complementary to the issue of energy performance of new constructions, a crucial role is given by contemporary policies to the role of existing assets, on the path for a sustainable community. The action on the building stock of the past is indeed *a radical way of doing less*, combining the benefits of technological efficiency with those related to the renewal of artefacts that are already built, though in the need of deep improvements and adaptation. 35% of the European building stock is older than 50 years, meaning also that a vast percentage of the European heritage is severely out of date in terms of performance, and might suffer from consistent problems of physical decay. The renovation of existing buildings can lead to huge energy savings, not only given the improved performance, rather also by reducing the CO_2 emissions that are commonly associated with the building industry. However, even though the EPBD acts addressed this issue since the early days, the share of buildings renovation is still far from the expectations: the official reports of the EU show that only a 0.4-1.2 (depending on the country) of the existing stock is renovated each year, all too few to guarantee the annulment of GHG emissions.

[06] Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market

[07] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (Text with EEA relevance)

[08] D.M. 26 giugno 2015, in materia di "*Adeguamento del decreto del Ministro dello sviluppo economico, 26 giugno 2009 - Linee guida nazionali per la certificazione energetica degli edifici.*"

Circular models for the building industry

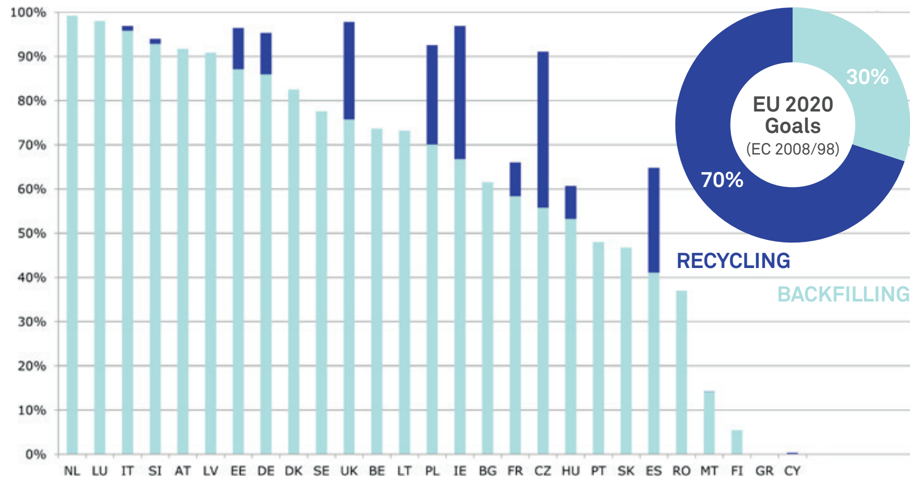
In order to enhance the share of old buildings being recovered, in order to promote a proficient market of maintenance, care, renovation and adaptation of the existing stock, the economic and social frameworks need to change first. The *European Green Deal* considers the development of circular economy models one of the key challenges of the next few decades. The concept of circular economy does not come from the AEC construction, rather from the design and manufacturing of consumers product: its main objective is to decouple economic growth from finite resource consumption, by adopting models of industrial production oriented to the reuse of waste and continual use of resources. **(Yeh, 2019)** As if they were part of natural cycles, technical components need to be reintegrated into productive cycles, and indeed also biological cycles matter, in order to allow biological matters to re-enter the cycle of decomposition (after that they have been used in man made products) without harming the ecosystem with pollutants or die hard synthetic parts. **(McDonough and Braungart, 2002)**

The transition towards a circular conception of the built environment has a two-fold preoccupation: on the one hand, the reuse and "re-cycling" of existing buildings, on the other side the control of the flow of resources. The first topic has already gained wide relevance, even though the concrete application of the principles is slow to become a widespread reality. Even though the activities of renovation are worth a 57% of the total activity of the building sector, only a minimum percentage of the existing stock, on a yearly basis, undergoes processes of transformation. Even though the environmental benefits are well known, some aspects are still discouraging a wider diffusion of projects for regeneration. Barriers might be financial (uncertainties about costs, lack of facilitated financing policies, low prices of conventional non renewable energy sources), technical (lack of technical solutions, lack of specialised knowledge of professionals) and include a number of hidden process barriers or regulatory barriers (fragmentation of the supply chain, ambiguous or controversial norms, lack of awareness of homeowners). The European directives EPBD and RES partially fail dealing with possible solutions to overcome these barriers, being rather concerned about setting the general targets in terms of energy performance and provision of buildings, whether new or renovated. **(Artola et al., 2016)** However, the EED (*Energy Efficiency Directive*),[09] in its article 4, defined the basics of actions to be laid down in order to put the EU member states on track: a statistical overview of the national building stock, identifying cost-effective scenario of renovation for the different climate zones and promoting policies to stimulate deep renovations of constructions, together with a long-term strategy to guide decisions of individuals and of the construction industry and an estimation of the expected energy savings. The national plans for regulation, financing and communication for the renovation economy have been submitted in 2017. **(Castellazzi et al., 2019)**

[09] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC (Text with EEA relevance)

Figure 03

Construction and Demolition Waste: material recovery and backfilling state (2011) and goals (2020)



[10] Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance)

In this respect, the growth of circular economy might be the missing link between the crucial issue of energy efficiency and that of resources (material and financial), where most of the different barriers to a circular built environment lie. The *Roadmap to a Resource Efficient Europe* defines the strategy and key challenges and targets in terms of resources flow management. In first place, its aim is to tackle those bottlenecks, inconsistencies, to ensure that all policies are going in the same direction, but also market (such as prices that do not reflect the real costs of resource uses) and cultural circumstances (lack of life-cycle thinking of all the stakeholders). One of the main concerns of the roadmap is the reduction of residual waste, by turning it into a resource, by stimulating the market and demand for recycled materials, by introducing minimum recycled material rates, durability and re-usability criteria and severely addressing the illegal shipment of hazardous waste. **(European Commission, 2011)** The issue is closely connected with the world of buildings: construction and demolition waste (CDW) is among the widest waste streams in Europe, worth in average 25-30% of the total amount (many count more materials and wastes as such, making the data difficult to compare). CDW often includes many different materials (concrete, bricks, gypsum, wood, glass, metals, plastic), many of which can be recycled: this makes of construction waste a priority in the European agenda and a new economic opportunity. **(Ec.europa.eu, 2019)**

The framework for waste treatment and policies dates back to 2008, with the *Waste Framework Directive* (WFD).[10] This provides a definition of the concepts regarding this problem and a waste hierarchy for future policies about waste treatment (prevention, re-use, recycling, other types of recovery, disposal). With regard to construction waste, the WFD defined the targets of materials' recycling for 2020, set to the 70% (by weight) of non-hazardous wastes (excluding some specific categories of materials that shall be reused, or undergo different processes other kind of recoveries). Finally, the topic of CDW has recently found its way to become part of the *Circular Economy Package*, a cluster of policies, guidelines and financing for the development of a circular AEC sector. **(European Commission, 2018b)**

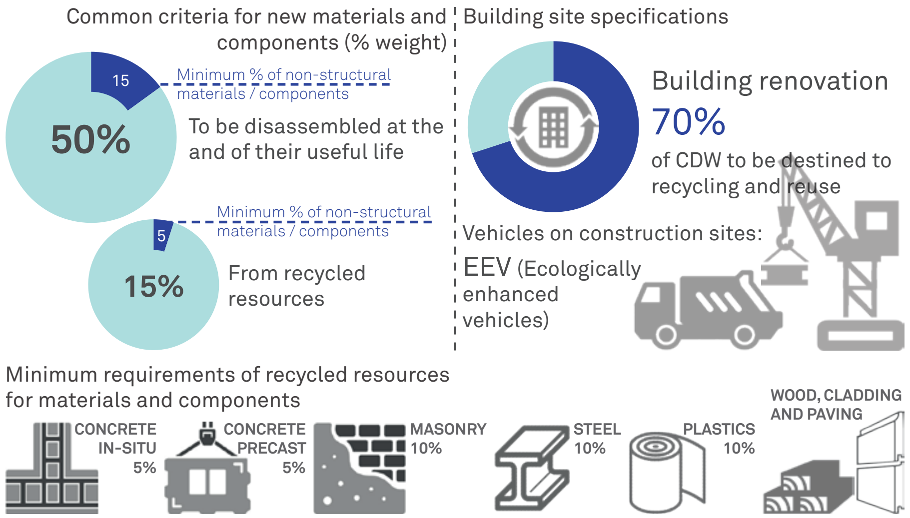


Figure 04

Recap of the *Criteri Ambientali Minimi* (2017)

The *Waste Framework Directive* assigned to each member state the task of developing adequate policies and strategies. As the Italian case testifies, however, the adoption of such measures happened all too often later than necessary. The WFD is adjusted to the national context in 2010.[11] The 2020 goal was however set to 50% (lower than the 70% requested by the EU directive). In addition, yet in 2017, *Legambiente* (independent Italian environmentalist association) reports how the state of the art is dramatically different from the previsions: even though there are no longer technical, performance or economic reasons to avoid the recycling of CDW and use of recycled materials, the ability to recycle of the Italian industries is worth a mere 10% of the 40 millions tons of waste per year. **(Legambiente, 2017)** Policies in favour of circular models have been reinforced in late 2015[12]. The fifth article reports the general provisions for post-use of materials, waste recovery and recycling: it is envisaged the introduction of financial incentives for the use of recycled resources, and the introduction of the CAM (*Criteri Minimi Ambientali*), minimum environmental requirements for production processes. Regarding the construction industry, the specific law was has been approved in 2017.[13] It provides norms regarding the entire spectrum of environmental externalities of new construction, renovation and maintenance of public buildings, including aspects regarding the resource flow. In order to cut the environmental impact, it is augmented to 70% the rate of demolition non-hazardous waste which must be initiated to recycling cycles or other forms of reuse or recovery. This aspect has to be included in the design stage, with a plan for the process of selective demolition (separation of the different materials, to allow their future employment) and transportation of materials. Severe environmental criteria are specified also for the transportation phase of the non-reusable component of demolition wastes, as well as for the new materials to be employed in the new construction or addition of parts to existing buildings. In this regard, it is introduced the concept of *renewable materials*, materials coming from renewable resources (for at least a 20% of their weight).

[11] D.L. 3 dicembre 2010, in materia di "*Disposizioni di attuazione della direttiva 2008/98/CE del Parlamento europeo e del Consiglio del 19 novembre 2008 relativa ai rifiuti e che abroga alcune direttive.*"

[12] L. 28 dicembre 2015, in materia di "*Disposizioni in materia ambientale per promuovere misure di green economy e per il contenimento dell'uso eccessivo di risorse naturali.*"

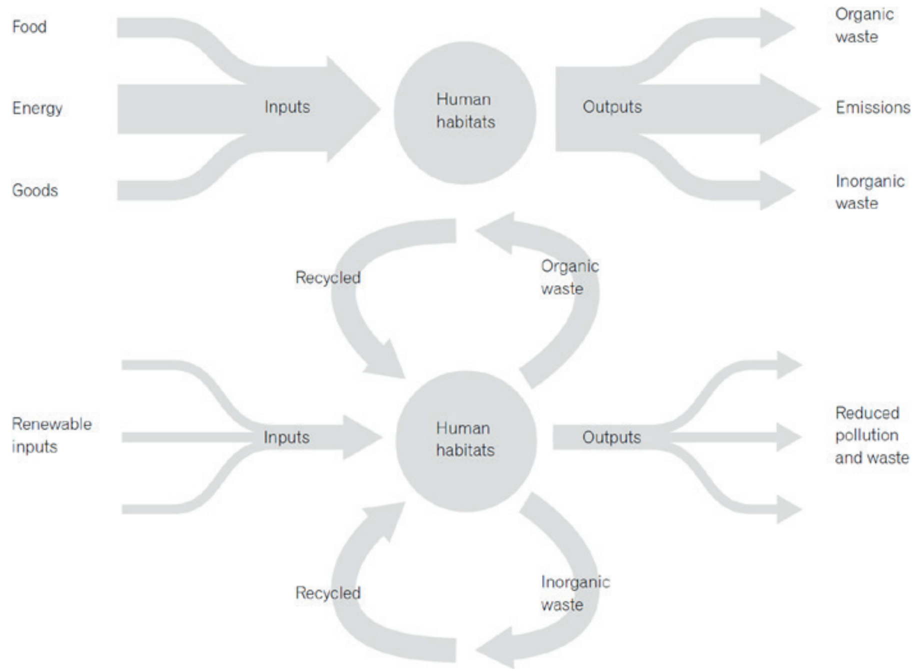
[13] D.L. 11 ottobre 2017, in materia di "*Criteri Ambientali Minimi per l'affidamento di servizi di progettazione e lavori per la nuova costruzione, ristrutturazione e manutenzione di edifici pubblici.* "

Figure 05

Cities' metabolism

Linear (above): high rate of consumption and consequential high production of pollution and waste

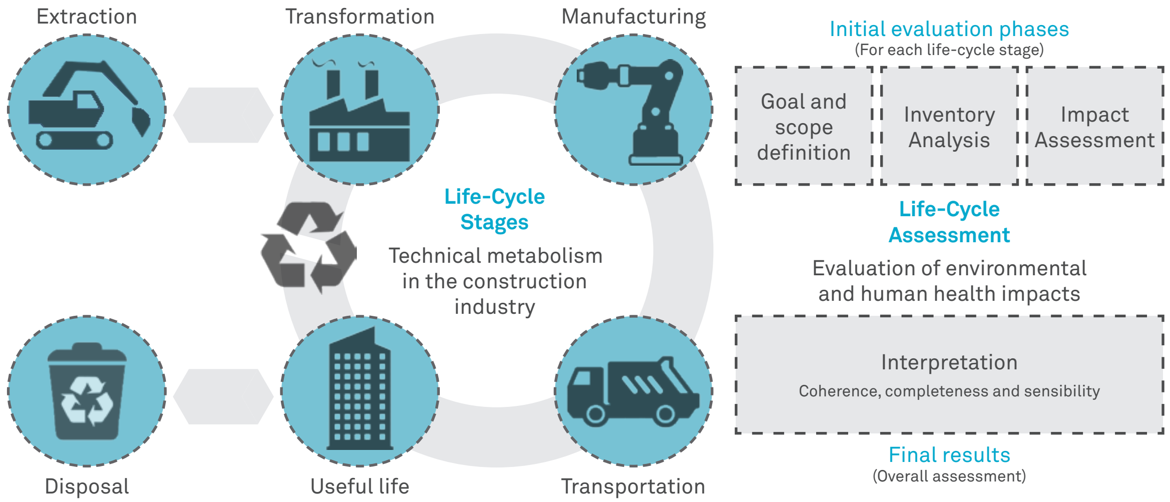
Circular (below): minimised inputs, most of which from renewable sources, and maximum recycling of artificial (technical cycle) and organic (biological cycle) wastes



Life-Cycle Thinking

The transition towards a low carbon, circular model requires a shift in the cultural perspective and understanding of cities, towards a metabolic model. A metabolic vision implies at the same time decline of the concept of waste, which, just as much as it happens in nature, should be regarded instead as nutrient for successive development. This necessity is the obvious result of the acknowledgement of the finiteness of resources, and therefore of the long-term outcomes of linear models of urban development. In this regard, the topic of energy efficiency alone is not sufficient to guarantee the sustainability of human activity, since, although contributing to the overall reduction of demand (energy, resources) and outputs (waste, emissions), it fails dealing with the causes behind these phenomena, that is to say the lack of foresight of a linear vision. **(McDonough and Braungart, 2002)**

The cultural challenge for architects and planners becomes, in the perspective of a gradual transition towards a circular model of economies, the devise of alternative approaches to the design of urban transformation. One big part of this challenge lies in the application of methodologies that are capable of assessing the environmental and human health impact of human activities. In order to achieve this result, the entirety of resource and energy flows must be considered: from the extraction of raw materials to their transformation and manufacturing of components, their transportation on site and use, and finally their end of life (disposal, reuse or recycling). The *Life-cycle Assessment* (LCA) is the methodology used to conduct this evaluation, through an inventory of the energy and resources of construction processes in every stage. **(Preservation Green Lab, 2011)**



The most innovative aspect of the LCA methodology is indeed a new way of understanding production processes as a set of operations, dealing with different flows of resources and energy input and output. The procedure is highly objective, as it has been standardised by the *International Standard Organisation* (ISO) in 2006.[14] It is based on an iterative process, which considers the different life-cycle stages, although discernible, closely interrelated and linked consequentially. Each LCA starts with the definition of an objective, which includes the definition of the functional unit being assessed, the system boundaries, the requirements in quantity and quality of data and the allocations method. This stage is meant to produce a flow chart of the different process units, linked by energy or resource flow connections: the set of process units depends on the system boundaries defined above. Subsequently, the inventory analysis comprehends the data collection, processing and assignment. Data can be classified according to their different origins: primary data (to be preferred) derive from direct measurements on the production site, secondary data which come from databases or software, and tertiary data, gathered from manuals, scientific publications or estimated values. Finally, the LCIA (*Life-Cycle Impact Assessment*) is thought to define the potential environmental and health impacts to be evaluated. Some criteria have to be considered while deciding the categories: completeness (to consider all the potential categories that the system might affect during its life-cycle), independence (avoid intersections between the categories) and practicality (still, to limit the number of categories in order to make the assessment more legible). The characterisation of the different impact categories is made thanks to the assignment, to each of them, of representative unit measures. This choice relies often on proven scientific models of environmental impact evaluation: for instance, the contribution to the greenhouse effect is measured by the quantity of equivalent CO_2. The results are than normalised in index, in order to allow for a comparison. Final stage of the LCA methodology is the interpretation of results, a number of final critic observation on their coherence, completeness and sensibility. (Maninchedda, 2019)

[14] ISO 14040:2006, "*Environmental management — Life cycle assessment — Principles and framework.*" and: ISO 14044:2006, "*Environmental management — Life cycle assessment — Requirements and guidelines.*"

Figure 06 (Previous page)

Life-Cycle Stages and LCA methodology phases

Left: typical flow of resources between construction stages (technical metabolism of building industry)

Right: phases of the standard ISO methodology for LCA

Born within the context of industrial production, the methodology's goal is to quantify the environmental impact of the entire life-cycle of a product or a service, to interpret the different impact of stages on the overall energy and resource flow, ultimately evidencing possibilities for improving the environmental quality of the product being assessed. Hence, LCA is not only to be regarded as a design tool, rather as an instrument to assist "greener" decision-making, communicate environmental information and comparison of products based on their environmental impact. However, it is possible to link all of these objectives with the decision making issues in the building industry, and in particular with the possibility of circular, metabolic conception of built environment. Although the LCA methodology is still hardly considerable as a conventional design and construction routine, its application might be particularly proficient in order to quantify, communicate and improve the environmental benefits of existing buildings renewal and reuse, beyond the obvious advantage of their performance improvement. It is estimated that the improved performance of a new edifice, built according to today standards, might take from 10 up to 80 years to pay off the impacts of energy and material resources employed for its construction. (Preservation Green Lab, 2011)

Boundary conditions

As a tool of confrontation, the LCA methodology is able to reveal the latent values of existing constructions, even if obsolete and poorly efficient, by comparing the life cycle environmental performance of potential retrofit scenario with those of potential substitution (demolition and reconstruction) policies of urban development. As a tool of communication, LCA can help spreading awareness about the impact of construction processes and allow standard certification systems to share these impacts: this is still a young field of application, yet it is possible to observe a trend of growing attention towards the thematic of resource flows. (Vierra, 2019) Some Green Building Certification programs, such as LEED v4 and BREEM provide additional credits for buildings which proof better environmental qualities, assessed with regard to their entire lifecycle. (oneclicklca.com, 2019)

The "environment" of policies, the evolution of the market, social and cultural contexts are shaping the transition towards a sustainable model of development and a circular model for economies and urban transformation. The aim of policies is to draw the boundary conditions of these processes, define priorities and envision strategies to achieve the objectives in a fair and transparent way: policy makers can pursue these goals by means of regulations, or financial and communication instruments. With regard to policies and the adaptation of the existing stock, each and every of these instruments is necessary to reduce the influence of barriers to change. The problem of *grandfather clauses* might be addressed, for instance, by introducing minimum energy performance standards for the entire building stock at certain conditions, and the introduction of refurbishment obligations in the case in which these requirements would not be satisfied. Another proficient field of regulation will increasingly be that regarding the limitation and efficiency in the supplying of primary resources, and the definition of severe rules regarding the recycling and reuse of materials and waste: besides the obvious environmental advantages, this kind of policies cannot help but making less desirable for developers to undertake demolition and new construction enterprises, rather at carefully evaluating the potential for reuse of existing buildings, which can count on a great value of embodied energy and city infrastructures already displaced. At the same time, these can reduce the expenses for the selective demolition and disposal of building material and components.

The topic of communication of efficiency, risk and impact of the built environment, the stimulation and obligation to the use of standard methods of certification and classification cannot help but to raise awareness on the issue and to reduce the ambiguities that accompany all too often the decision making in terms of building retrofit, by supporting it with clear and comparable data and information. Finally, connected to this aspect, the introduction of financial measures in order to stimulate the independent growth of a maintenance, regeneration and retrofit market of the existing stock. Subsidies and financial incentives, tax credits, but also subsidies to research and clean energy companies are among the most promising strategies, to be considered with regard to the specific national or regional context. The influence of a public intervention on the construction industry and market, although being a necessity, must be carefully calibrated, in order to avoid injustice and the eventuality of frauds. (Artola, 2016) Therefore, rather than by directly injecting financial capitals (also, a condition that is high unlikely to happen, in an era of gradual impoverishment of public funds), it can be pursued both by giving positive examples (the policies of *Green Public Procurements*) and addressing the control and definition of those market's boundary conditions (the costs of material and energy resources in first place), often the most decisive aspects for homeowners or investors in order to decide their strategies of development.

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01.4 RE-CYCLING: THE FUTURE OF DWELLING

Perspectives of urban regeneration

The future of European housing lies in its past. It is nowadays widely acknowledged that the vast majority of future dwellings is already built. What is generally known as urban regeneration, it is less part of an analytical concept than of a cultural standpoint, one that implies the recognition or denial of some implicit values of existing artefacts. Put into practice, three main categories of operation have shaped the activity of urban regeneration since the early days: the renovation of city centres, the reuse of abandoned buildings (such as former industrial areas) and, finally, the renewal of huge, mono-functional residential complexes (such as those built in the second half of the XX century all over Europe). This latter, the integration of obsolete housing quarters within the contemporary city is probably the hardest challenge for European cities, both in terms of quantity (given the wide diffusion of post war housing complexes) and of cultural relevance (their integration with current city models). **(Bodenschatz, 2003)** The shift towards a culture of regeneration, however, is a substantial transformation: it implies an action *with* the city, rather than an action *on* the city. It requires, in other words, to deepen the knowledge of material and ephemeral features of a specific context, and of the technical means to act on this realm. Its design addresses those situations of decay and conflict between past, present, future and, by providing a transformation, it empowers places and inhabitants to respond to the varying expectations and challenges of contemporary societies. **(Galdini, 2008)** Cities face three main challenges: a socio-economic one, an environmental one and one regarding the urban space itself (shrinking cities, crisis of identity of the public space, physical obsolescence). Urban regeneration addresses these issues of contemporaneity by recognising that the existing assets hold an implicit potential (material, infrastructures, memories) that has already been displaced, and that will allow these to undertake many other lifecycles even after their apparent actual decay. It is as well a bold metaphor with biology, where cells (buildings) that are able to regenerate contribute to the regeneration of tissues (urban fabric) and finally of body parts (districts, neighbourhoods). These goals require practices and projects capable of re-activating, re-start the apparently dormant potential of existing urban fabrics. It requires the definition of new models of development for communities and all the stakeholders involved in the transformation, based on the circularity of processes and new models of governance (such as active participation of the inhabitants). **(D'Onofrio and Talia, 2015)**

Figure 01
Demolition of *Khrushchyovka* blocks (Moscow, 2017)

[01] Colloquial name after the Soviet leader Nikita Khrushchev (1894-1971), who launched the mass housing development. *Khrushchyovka*, although already experimented in the early 40s, became a large scale model only since the second half of the 50s.

A new era of urban renewal through expansion is nor desirable or tolerable in environmental terms, nor expectable with regard to socio-economic and demographic projections, at least in advanced and vastly urbanized western countries. The rising degree of obsolescence of the European building stock leaves only two distinct possibilities. On the one hand, demolition and substitution: a radical approach that, in recent decades, has found its way to become the standard for many European cities. Well known in this regard is the Soviet urban planning, which made a trademark of this operation, based on a complete reconstruction of entire districts of cities, formerly dominated by the ceaseless repetition of the same housing block, from Beijing to East Berlin. It is the case of *Khrushchyovka*,[01] low rise and affordable residential blocks that were planned as a temporary solution for the dwelling's shortage in the USSR, at least until the expected final resolution of the issue with the advent of mature communism. Most of these blocks were built according to a design useful life of 25 years. In order to achieve the maximum of affordability, these apartments were erected as 1:1 life-scale experiments of heavy prefabrication techniques, such was the fast assemblage of pre-stressed concrete panels (*Plattenbau*). Built with a maximum of 5 storeys, which redeemed them from the need of an elevator, they provided poor service and common spaces, inconvenient walk-through rooms, low ceilings and negligible heat and sound insulation. In 2017, Moscow's major Sergey Sobyanin declared city's commitment to put into effect one of the most extensive resettlement programs in history, involving the demolition of 7900 blocks, corresponding to a floor surface of 25 millions square meters (an overwhelming rate of 10% of the city's residential estate) and to a public expenditure of 300bn roubles (42bn Euros). **(Luhn, 2017)**

The complex resettlement of about 1.6 million inhabitants, however, depicts the inevitable ambiguity and controversy of the operation of substitution. The promise of apartments at least 20% larger, overall better neighbourhoods and construction standards does not find consent among all the residents of the old soviet blocks: some are frightened about the speculative character of the operation, some do not really trust the promise of improved living conditions. Some others, well bound to their old neighbourhood and dwelling (who eventually improved and personalised it over the decades) feel this process as a condemnation, an unpleasant imposition. (Mikhaylyuk, 2017)

> *«The replacement of a building is an action that derives from an assumption of obsolescence and can be motivated by structural, technological, functional, typological, economic and social reasons. [..] respond to a transformation of needs, new ways of living, new lifestyles and functional mixes, [..] starting from a careful reading of the places where they are.»*
>
> [Montuori, L. (2019). *Sostituire l'architettura*. Costruire in Laterizio, 181, pp.10-11]

Urban regeneration has not always meant radical resistance to urban substitution, rather it often implied the demolition and reconstruction of ageing residential quarters, in particular in those cities that experienced strong phenomena of shrinking in the post industrial era (such as Berlin). (Bodenschatz, 2003) For, if substitution responds to a transformation of needs, the same goal can be perceived by a wide and diverse range of practices, committed to the avoidance of the demolition of existing heritage: an alternative option, the design for re-cycling at a urban scale, thought to guarantee new life to old buildings and cityscapes. The rise of an impelling demand for an enhanced environmental quality in the processes of urban transformation inevitably shifts the attention on the regeneration of assets that already exist. Although not always possible, a radical approach in the design for urban regeneration has risen in recent times, one that in fact aims at recognising and praising the values of existing urban contexts, even when strongly underestimated or in decline, being the project of regeneration a tool, able to create new values from the ashes of the old. The Estonian city of Tartu, second most populous town in this country, shows that a second way of dealing with the problem is possible: within the broader context of the European research *SmartEnCity*, the municipality undertook a generous amount of policies in favour of a sustainable transition of the city towards a *Smart Zero Carbon* mode. Huge part of this transition, in fact, must be achieved by retrofitting the obsolete Soviet residential complexes: in this respect, the public administration provided a "retrofitting package", including both a list of technical retrofit scenario and financial measures (an inclusive business model), oriented to support and co-found the transformation of a pilot sample of 17 existing *Khrushchyovka* into the so-called *Smartovka*, energy efficient, liveable and renewed residential neighbourhoods, that will be able, eventually, to inspire the community to develop environmentally aware lifestyles. The entire plan provided the participation of the inhabitants in the decisional process. (Smartencity.eu, 2020)

Figure 02

Regeneration of a *Khrushchyovka* block into a *Smartovka* (Tartu, Estonia)

The retrofit program undertaken by the city of Tartu included the participation of inhabitants in the decisional process, as well as in some stages of the renewal process, such as the mural painting of some of the building blocks.

A culture of re-cycling: the modern habitat

If urban regeneration is to become the main paradigm of cities renovation, the re-cycling (retrofit) of existing buildings must be accounted as a large-scale strategy of urban development, one able, indeed, to substitute the traditional new construction or demolition and reconstruction routine. For, if the regeneration of the existing stock is based on the necessity for an improvement of efficiency, the possible extents of renovation depend on the nature of an asset and on its recognised values. Far from being declined only in economic terms, the value of a buildings implies also the cultural and collective values that are credited to them. (Gaspari, 2012) This topic becomes of particular importance in respect to the heritage of the second half of the 20th century, the modernist housing heritage. For, if the reuse of vast, urban industrial areas of the early 1900 (which were dismissed commonly since the late 1970's around entire Europe as a consequence of the decline of the Fordist society) dominated the architectural debate in the last decades and at the turn of the new century, the landscape of large scale settlements that arose all over Europe in the time frame of a few decades, to overcome the housing shortage brought by the disruptions of the Second World War and by the impetuous economic and demographic growth of western cities that followed, has abruptly become the main issues for contemporary cities. Accordingly, just as much as it happened in respect to the issue of the dismissed masterpieces of industrial architecture, their post-use value for the city and its inhabitants, a new architectural debate must address the issue of the ageing stock of modern mass housing, about its cultural and strategical value for the development of future cities, framed also by the inevitable shift towards a new deal based on circularity, resilience, adaptation and sustainability of the built environment.

The different collective values ascribed to a neighbourhood or a district are indeed the result of specific cultural circumstances, of the object's history itself and of the momentary perception and expectations of the inhabitants and, last but not least, of its economic value and social reputation. Symptomatic of the wicked ambiguity around the perception of modernist heritage is the vicissitude of the *Hansaviertel* district in West Berlin, part of the *Interbau 1957* international exposition. The reconstruction of the former district, destroyed during the World War, became a field of experimentation for the 53 internationally renowned architects that took part to the exposition. The aim was in fact to gather the international attention on the modernist post-war residential reconstruction, not without any political intention, a response to the Soviet reconstruction in *Stalinallees*. Though to the positivist rhetoric that echoed the exposition, many criticisms followed shortly after its completion. From ideal city of tomorrow, the imminent change of perspective of postmodern culture transformed this complex, within a few decades, into a run-down example of the failure of modernist urban planning. Yet, the all peculiar experimental and historical value of this district allowed, in recent years, for a rehabilitation in collective perception. It is now part of the listed heritage of Berlin, and since the 90s. As citizens started appreciating the suburban character of this green, low density neighbourhood, the vacancy rate is lower than ever since the 90s (when most of dwellings were emptied out), regardless of the higher and higher market and rental prices of the apartments. (Lautenschläger, 2017) However, this would have not been possible if the city's administration did not undertake a campaign for the retrofit of these dwellings: within a few years, 1160 have been renovated, guaranteeing maintenance and an adequate degree of energy and functional efficiency. The direction that has been firmly undertaken by the administration body for *Urban Development and Housing* in Berlin relies on the acknowledgement that bounding the issue of listed heritage preservation to that of its environmental impact and of its market revaluation is key in order to achieve the adaptation and survival of the existing urban fabric. (Krau and Vallentin, 2013) Explanatory is the case of the residential towers in *Bartningallee*, in particular that designed by the architects Raymond Lopez and Eugène Beaudouin between 1956 and 1957. A design in which radical experimentation played a key role: operable partitions were meant to allow new, flexible life-styles, a common topic of research for architects at the time, with a view to a strong uncertainty about future (near or far) models of development. Their conception embodied also the idea of technical devices as servant elements of buildings, and their circulation showcased by the structural and architectural grid of elements, in the interiors and on the facade. Consistent part of the research of these architects moved towards the issue of industrial heavy prefabrication, as of the one and only construction method allowing the achievement of a consistent translation into reality of the ideals of a mass standardisation, yet flexible, adaptable to the needs of the user. (Hansaviertel.berlin, 2020)

Figure 03
(Next page, left)

Brenne Architekten, retrofit of the residential tower in *Bartningallee 11–13* (Berlin, 2008)

Actual state of the building, after the conservative retrofit operations

Figure 04
(Next page, right)

Frédéric Druot and Lacaton & Vassal, transformation of the residential tower *Tour Bois-le-Prêtre* (Paris, 2011)

Building after the transformation process: a radical make up of the envelope, ultimately granting the regeneration of the entire residential block

The great difficulty and relevance of the retrofit operations on this building lied, in fact, in the all peculiar mix of technological and structural solutions employed by the architects, surely a crucial aspect of the final, remarkable aspect of this post-war building. The preservation of the trademark exterior heating pipes, as well as of the modular steel elements of the facade (integral part of the conception of this building) were chosen as elements to be preserved at all costs. The accurate study of the actual state of conservation showed that a great part of the existing windows had already been substituted by plastic framed ones, clearly more efficient, as well as the protective shell of thermal pipes. These modifications had happened before of the recognition of this building as listed heritage. The flexible and adaptable character of the interior distribution (a valuable feature also with regard to contemporary living habits) become another aspect whose preservation deserved a particular commitment by the architects. Even considered the high degree of substantial decay of the building's structure and components, which inevitably led the management to undertake the retrofit project, the design team opted for a less comprehensive approach to the renovation: rather than the introduction of new elements, the restoration of the original constructive elements, rather than an invasive intervention, its avoidance, reducing the harm for the original character of the building. However, it has been decisive the radical commitment by the designers to propose a long term solution, rather than a temporary repair: a new life-cycle for a masterpiece of post-war modernity. (Brenne and Hoffmann, 2012)

Interestingly enough, another residential tower designed by Raymond Lopez himself just a couple of years later has undergone a similar vicissitude. The *Tour Bois le Prêtre*, a 17 stories high rise built between 1958 and 1961, stands a few steps away from the *Boulevard Périphérique,* in the northern outskirts of the metropolitan area of Paris. Belonging to the public body for affordable housing development (*Paris Habitat*, the Paris *Office Public de l'Habitat*), this building was, already in the late 90s, on top of the demolition list of the administration, in a vast project of urban renewal through the elimination of some large-scale settlements of the relevant French modernist public housing heritage, facing a relentless physical and social decay. The building somehow survived these dreary intentions: in 2007, on the wave of a shifted sensibility towards this type of heritage, the architects Frédéric Druot, Anne Lacaton and Jean Philippe Vassal proposed a strategy for the regeneration of this high rise block to OPH, in order to avoid its demolition and, instead, to adapt the rental offer of the existing dwellings to the current estate market. Their approach enabled to transform the entirety of the 96 flats of the tower, adding 8 new dwellings and enlarging or remodelling the existing ones with the external addition of winter gardens and balconies, ultimately achieving an all improved variety of apartments, common services and up to date energy efficiency levels. The project made it to become a reality: the retrofit works ended in 2011, after that a complex process of participation of the inhabitants had been completed before of the definition of the final draft: the tenants were allowed to define the configuration that best fitted their financial resources and expectations about this transformation. (Druot, Lacaton and Vassal, 2007) Background to Druot and Lacaton & Vassal's proposal is a profound shift in the perception of post-war habitat: their intention is to put forward what is positive about this heritage, rather than the mere denounce of its bad side so often kept on, as the history of these two buildings can testify. A vision of renewed interest, respect and generosity towards daily life of these neighbourhoods, which must be considered exceptional terrains of past and, hopefully, future experimentation on the issue of dwelling. The relevant differences between the two recent vicissitudes of these modern buildings, with particular regard to the architectural outcome of the regeneration practice, attest that a culture of re-cycling existing buildings does not necessarily needs pre-determined approaches nor prescriptive solutions, rather that these are subordinated to the boundary conditions, the perception of the building itself and expectations of a community about future urban transformations. While the first adopted a rather conservative approach, minimising impacts on what exists in order to reduce impacts of the transformation, the second path aims at maximising the outcome, by taking on a more radical vision of the future. What both projects clearly affirm, however, is that a renewed care for the physical side of buildings is not only necessary to guarantee their survival, yet also to generate new cultural, social and economic values: that architecture is a resource beyond its passing cultural meaning.

More: the regeneration of revenue

The retrofit challenge ultimately coincides with the ideal of reconciling the regeneration of existing residential space with the production of urban space itself. More than ever, this issue is crucial in order to achieve the environmental sustainability of urban transformations: cities should take on this vision, in order to improve the liveability of the existing urban fabric, reinforce safety and functionality of the built environment. The benefits for this operation should be sought for in the improvement of built and environmental quality (structural safety, accessibility, energy efficiency and independence, reduction of pollution) and, therefore, of the attractiveness of a urban context. The externalities might have huge effects on urban communities (improved social diversity and inclusion) and for the construction industry, having hard times to find opportunities for growth in the market for new constructions. (Moley, 2017) Cities have been a crucial concern for the European Union policies around sustainable development, since the early days. The first vision and framework for action about urban development dates back to 1998, defining the key objectives for cities of the XXI century: strengthening their employment rate and economic prosperity, promoting equality and social inclusion, protecting and improving the quality of the environment and contributing to cities administration and governance. (European Commission, 1998) However, the potential for action of the public administration of cities is all too often dramatically limited. The recent financial crisis has brought to the surface this issue: its impact on the private estate market has relegated the role of urban housing development to the margins, market value of dwellings has shrunk rapidly and in accordance with the reduced ability of tenants to pay the rents, and eventually to buy a new home. The portrait is not consolatory with respect to the landscape of public housing: the selling of publicly owed dwellings has become the standard solution for administrations to earn from an ever more financially demanding activity. A large-scale public intervention in the development, improvement and management of the residential stock, of such an impact as that of post-war reconstruction, is nowadays hardly expectable. As the relevance of the public administrations as financial lender shrinks, the role of a governance will be more and more that to define the "rules of the game", to create the promising conditions to let the transformation take on its course, and to control the quality of this process in order to make it environmentally and socially sustainable. The crucial task of vitalising the private investors and professionals in this process is the key challenge, though it will be necessary to understand this transition; two key challenges must be acknowledged and firmly addressed: the definition of measures and frameworks for the speculative market in order to enhance the urban quality, and the promotion of private initiatives of social housing, addressing the issue of economic inclusion of the urban residential habitat and the necessity for different modes of access and flexibility which drive a completely renewed contemporary market demand. (Perriccioli, 2015)

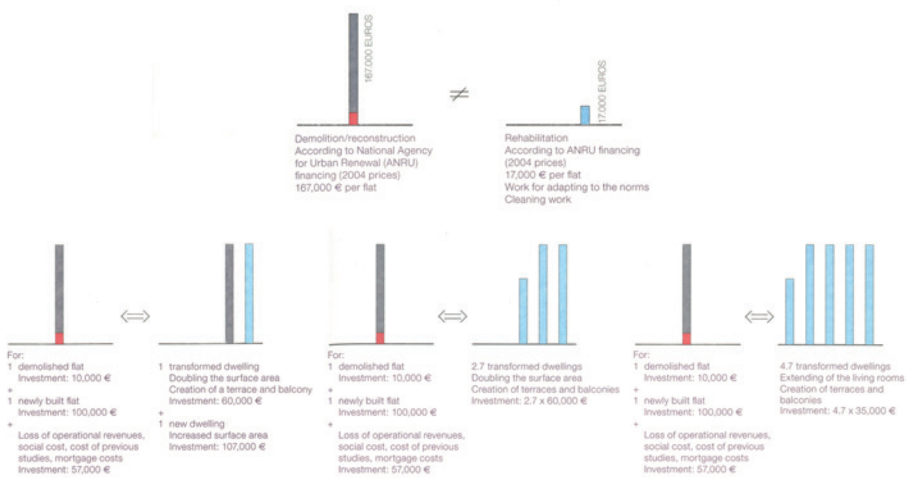

Figure 05

Lacaton & Vassal, *A statement of accounts*

Comparison between the typical operations by the public administration and different perspectives of large scale regeneration

The design for regeneration often offers the possibility for mixed, innovative approaches, not solely in technical terms, rather also in terms of social, economic practices that shape its development process. It acts not only on an existing physical decay, rather also on the concrete problems of the day to day life of inhabitants. It offers a remarkable opportunity of achieving more by doing less, to solve hidden, wicked problems of urban life not by denying or cancelling them, rather by shifting one's attention on their hidden, undisclosed potential. (Petzet and Heilmeyer, 2012) This vision lies at the core of Lacaton & Vassal's proposal for a large scale transition of the policies of urban residential renewal towards the reuse and recycling of existing spaces. Aside from their technical contribution, an additive approach aimed at maximising the positive impact of the regeneration while minimising the negative one of the process for the inhabitants and collectivity (in terms of construction, costs, resources), their vision embodies a financial perspective for an economy of scale of residential regeneration: role of the architect is to devise solutions, case by case, which, reducing the marginal cost for the rehabilitation of each dwelling unit, will be ultimately able to reduce the amount of resources needed to achieve the transformation. The exceptional case of large-scale modern residential districts, hence, seems to be the most suitable to achieve the maximum of outcomes, since with a single action it will be possible, at the same time, to achieve a surplus that is proportional to the units interested by the process. The savings are to be found in the avoidance of the demolition and reconstruction, of the relocation of a large number of inhabitants and in the reduction of construction times and marginal costs for the retrofit of each residential unit. The maximisation of benefits will be manifested by the enhanced market value and attractiveness of dwellings and neighbourhoods, given the improved functionality, efficiency, accessibility and liveability. They propose an evaluation model that, accounting for all of these aspects, will evidence the convenience of rehabilitation if compared with traditional urban transformation practice. (Druot, Lacaton and Vassal, 2007)

The contribution of the French architects, although referred to the context of the French public housing, is worth of great attention also with regard to the issue of the regeneration of private assets, since it addresses, in addition to the physical one, the issue of the regeneration of revenue of the urban fabric. The traditional politics of governance exploited the selling of empty building plots and the urban taxation to make up for the increasing expenses and inefficiencies of the public sector. The result is an estate market unable to create surplus, if not by the positional value. However, when the sensibility about urban transformations shifts towards new expectations of environmental, social and economic sustainability (i.e. the limitation of land consumption), or the private market encounters a crisis (such as the global financial crisis started approximately in 2008), this system is brought to collapse. The question for urban planners and stakeholders becomes where to find this surplus: the answer is the reuse and re-cycling of existing assets based on the regeneration of revenue. (Rusci, 2017)

The revenue is the annuity that a user raises out of his use of spaces. This value is way less dependent on the specific contingencies of the estate market than the speculative one: this is the value of regeneration, which does not need new land to be produced, rather it always requires new, more efficient or valuable uses. The residential market presents in this respect some specific traits: in first place, for the traditional association of the residential property with its estate value safe growth (connected to the inflationary system of advanced economies). Yet, the estate crisis hit this model of growth in first place, adjusting the value of residential assets to ever lower amounts, for years; although signs of recovery have manifested in recent times, a revision of the construction market has proven necessary. Furthermore, the progressive deterioration of the solid relationship between revenue and localisation, consequence, for the most part, of the computerisation of commerce. Localisation, however still matters, only at a different degree: less based on common speculative tendencies, rather on its latent potential to cluster use values and productive or creative energies, and minimisation of friction for these forces. While in traditional speculative systems the value of estates is a function of the objective demand and offer on the market, the use value is subjective and connected to the potential productivity that a good assures to its owner. It is a latent value, which can only be disclosed with a transformation: the better the functional, physical and organisation features achieved, the higher the value and surplus will be. For this transition to happen, the canonical operation of restructuring, recovery and renovation is not enough; a regeneration, instead, can only be truly effective if able to activate the dynamisms of revenue of the assets being transformed. The *differential rent* must become the reference for urban regeneration practices. (Rusci, 2017) Architecture, in this light, should question traditional practices, in order to generate new values by improving the quality, efficiency and functionality of existing spaces, while questioning present organisation structures of traditional models of transformation.

Two perspectives of this challenge are of particular interest. A technical and cultural one, which implies the experimentation of methodologies and approaches suitable to the different cultural values of buildings to be preserved and apt at achieving the expected levels of efficiency, safety and comfort. It is now possible to observe a casuistry, a state of the art of regenerative practices. These are very often oriented to the improvement of the environmental values, to empower the users with up do date comfort standards, unknown at the moment of construction of the objects being retrofitted. Most of these projects share a common, radical approach: the intervention by means of lightweight and dry-layered construction technologies. These additions are often declined by means of a strong contemporary architectural language, hence clearly discernible from the initial configuration of the building. (Scuderi, 2019)

Second, but not of least importance, the social and economic side, concerning the models of development and organisation structures that lie in the background of urban regeneration. The feasibility and success of these interventions requires often the design of interations between different stakeholders: the inhabitants, possible investors, contractors and professionals. This side is of particular importance not only in terms of financing and supporting the project of regeneation, rather also it underlines the social character of the practice of regeneration: involvement and participation are design tools that can boost new economic possibilities for building and communities integrated renovation. (Nägeli and Tajeri, 2016)

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ADAPTIVE EXOSKELETON

02.1 DEFINITION AND DEVELOPMENT

Evolution of skyscraper typologies

Nature is able to produce an infinite array of solutions. We all roughly know how our body works structurally: our skeleton, made of mineralized tissues, provides us with the strength and stiffness that we need for our movement and support. While modern reinforced concrete/steel frames, ubiquitous in our cities, may recall and are in fact often compared with the *endoskeleton* of animals and men, many living beings show a different support system. It is the case of many insects and crustaceans that evolved with an external support system named *exoskeleton*. The root of the word obviously derives from the Greek *éxo* "outer", but they may often be referred to as shells, with all in all similar features of protection and support. Often made out of *chitin*, a derived of *glucose* made of a long-chain polymers of *N-acetylglucosamine* (about twice as stiff and six times stronger than *tendons*), they provide the connection with the muscles of the hosted arthropod, but they can also be suited for energy storage to allow some particular movements (notably the jump for locusts). The chitin fibres are embodied in a protein matrix, which may contain other mineral crystals to enhance the compression strength (whilst chitin is mostly stressed in case of traction thrusts). These "natural devices" merge the structural features of the skeleton with the features of protection, regulation and sensation of the skin. The different functions are guaranteed by the structure of this skeleton itself, composed by different layers. **("Exoskeleton", 2019)**

Anyway, it is probable that Fazlur Rahman Khan (1929-1982), Bangladeshi American structural engineer and architect (notable employee at *Skidmore, Owings & Merrill*) didn't think of insects while designing the 42 story high *Dewitt Chestnut Apartments* building in Chicago, completed in 1965. 120 meters tall, this skyscraper in known to be the first to experiment the structural typology *braced tube*, derived from the idea that the entire perimeter of the highrise building might contribute to the overall stiffness of the structure to lateral loads. It is as well the first application of an external support system in construction, in the history of tall buildings and contemporary architecture since the introduction of the modern structural materials (reinforced concrete and steel). **(Kahn, 1969)** The further evolution of this concept, led by Kahn himself with his lifelong partner at SOM Bruce Graham, brought to the conception of the *John Hancock Center* (875 North Michigan Avenue, Chicago, 1970), with its diagonalized-tube system that allowed for wider openings over the facade, and the *Sears Tower* (today known as *Willis Tower*, Chicago, 1974), thought as a bundled-tube of pre-

Figure 01

Skidmore, Owings & Merril, *Dewitt Chestnut Apartments building*, Chicago, Illinois, USA

The first remarkable example of a framed tube type external structure, completed in 1965.

assembled steel sections, which became for years the tallest building in the world with its 110 stories (440 m of height). These all time masterpieces gave an incredible impulse to innovation in highrise building. However, Khan gave also his remarkable contribution to the classification of highrise structural systems: in 1969 he proposed the first framework ever for classification of skyscraper's building types (updated in 1972 and 1973), used since then by most of the researchers striving to define the typology and evolution of skyscrapers. **(Ali, 2001)** The classification made is shown through *Heights for Structural Systems* diagrams, valid both for steel and reinforced concrete structural types, with the idea to propose a guideline for future designers of skyscrapers. Each typology has a wide range of height applications, depending on design and service criteria. Furthermore, two categories were proposed as a basic for the distinction between supporting systems, based on their position relative to the building perimeter: interior or exterior. **(Ali and Moon, 2007)**

Interior structures have been used since the early days of tall buildings design, with the advances introduced by the *Chicago School* at the turn of the 20th century. Early American skyscrapers took advantage of the progress in steel and concrete construction by adopting the *Moment Resisting Frame* typology. In *MRF* a system made of pillars and girders resists to stresses mainly through flexural stiffness of its members. Hinged frames were rapidly substituted by the rigid frame types. A second evolution consisted in the *Braced Frames*, to which additional lateral stiffness is guaranteed by *shear trusses* or *shear walls*. An alternative to concentric braces (with their typical configurations as single diagonals, cross-bracings, K or V bracings) are the *Eccentric Braced Frames*, which trade off an overall reduction of the weight efficiency (minor stiffness) with an increased ductility: a distance is left between the connecting points of frame and braces, making it possible to absorb energy through plastic deformation and, ultimately, through the formation of plastic hinges., a typology that has been, for this reason, widely used in seismic areas. Third possibility, as well as a great improvement in the possible height of skyscrapers, was granted by the combination of them two in the *Shear Wall/Truss-Frame Interaction System*, in which the proper lateral stability is obtained combining the approximately linear shear-type deflected curve of the *MRF* with the parabolic cantilever sway of the shear walls or trusses. **(Kahn and Sbarounis, 1964)** Althought these typologies defined the support system of most of the milestones of the early *American Building Type*, for greater heights the resistance of the core system becomes progressively inefficient. The advances in structural engineering introduced the so-called *Outrigger Structure*, in the form of stiff *header trusses* inducing tension-compression couples, ultimately granting the continuity of efficacy of the interior typologies up to much greater heights. **(Ali and Moon, 2007)**

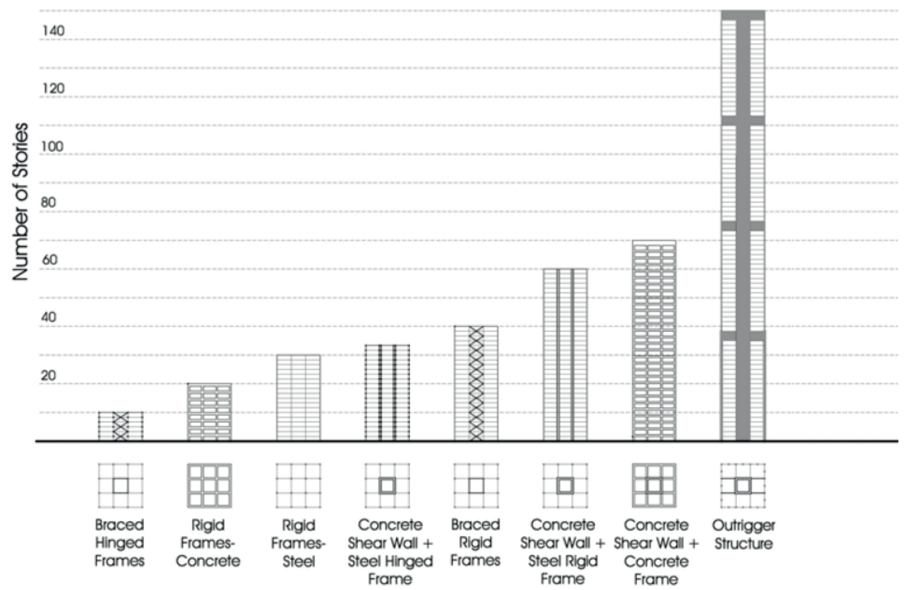
In the design of tall buildings, the main action to care about is that due to lateral forces. Called the *Premium for Height*, it is the tendency of highrise

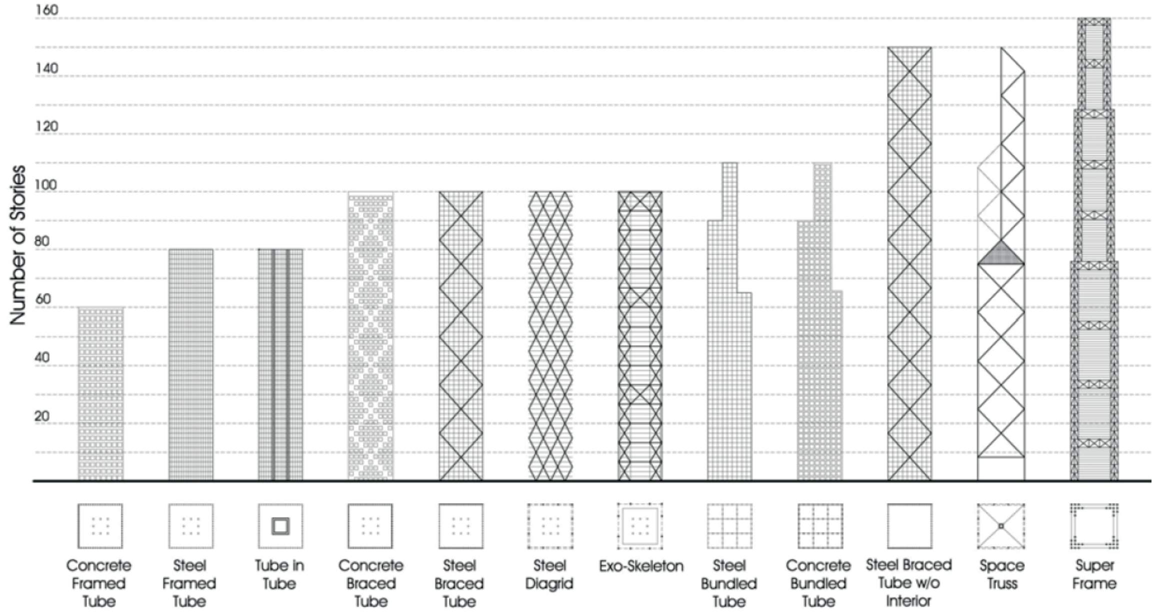
Figure 02

Height for Structural Systems **updated diagrams.**

Right: structural typologies of interior frame structures.

Below: typologies of exterior structures.





buildings to become improper, in terms of resources, when exceeding the limits in height imposed by their structural typology. A tower is a cantilever, fixed at the ground, free spanning in the air against wind and earthquake actions. It is for these reasons that, above a certain level, the effort required to develop the necessary overall shear and bending strength starts to raise at a parabolic pace: the weight (and cost) for the structural material outweighs the obvious economic advantages of skyscrapers. It is with this problem in mind that Kahn developed the first exterior structure: it is desirable to concentrate the structural capacity of a tall building at its perimeter, thus increasing the overall cantilever depth.

The *Framed Tube* made use of narrower and closer vertical struts, spanning vertically from storey to storey, where a *spandel beam* connects the vertical elements and supports the floors' diaphragm. Noticeable limit, as well as main driver for the subsequent developments of this concept, was the so-called *shear lag* effect: due to the nature of the *Framed Tube* as an approximation of a solid-wall tube, when subject to lateral forces the distribution of compression and tension stresses among the two flanges loses its expected linearity. Most of the thrust is gathered by the corners of the building's perimeter. The purpose of a good tube design became therefore to minimise the *shear lag* phenomenon, which was compromising the cantilever-like behaviour, as it was enhanced by the increase of the building's height. Again, the tendency for this typology to become disadvantageous at increasing heights (with beams and columns start being controlled by bending actions) led to a further innovation. The first solution was designed few years later (1970) in the *John Hancock Center* tower, which introduced colossal diagonal braces to stiffen the perimeter frames in their own plane. Besides the improvement in the building's height, the *Braced Tube* typology offered a new opportunity for the facade design, since the distance of the vertical struts of the tube was not constrained anymore by the need to induce the tubular behaviour. (Moon, 2018) The taller a building goes, the wider the base has to be, in order to grant the desirable slenderness of the tower. With this simple, yet effective rule Kahn and Graham designed the Seals Tower. This skyscraper is a *Bundled Tube* of 9 tubular structures, formed by stacked pre-fabricated steel tubes. The efficiency and architectural quality of this skyscraper made of it not only the tallest building on earth for many years (1973-1998), but also one of the most remarkable and rightfully devised models for highrise design since that very moment on. Last but not least, the popularity of the *Tube-in-Tube Systems* grew over the years: an inner tube confer the exterior tube additional stiffness and forms a service shaft. (Ali and Moon, 2007)

The diagrid type: diffusion and technology transfer

Starting from this era of great innovation at the turn of the seventies, the lateral system came nowadays to be considered the defining characteristic of any tall building. The tower needs to be stiff enough to resist efficiently to buckling under the combined action of gravity loads and wind or any other exceptional lateral action (earthquakes or impacts). It is in the definition of the lateral resisting system that lies the art of designing tall buildings, and the definition of the lateral system is mainly defined by the *shear system*. (Baker, 2015) Architecture and engineering firms started prototyping new typologies that would not just be more efficient, rather more architecturally appealing. Turning the structure of skyscrapers inside-out resolved in a new research on structural shapes, together with the new development in terms of technology of facade construction. The aesthetic qualities of braced structures, tested in the *John Hancock Centre*, was to become one

Figure 03
(Next page, left)

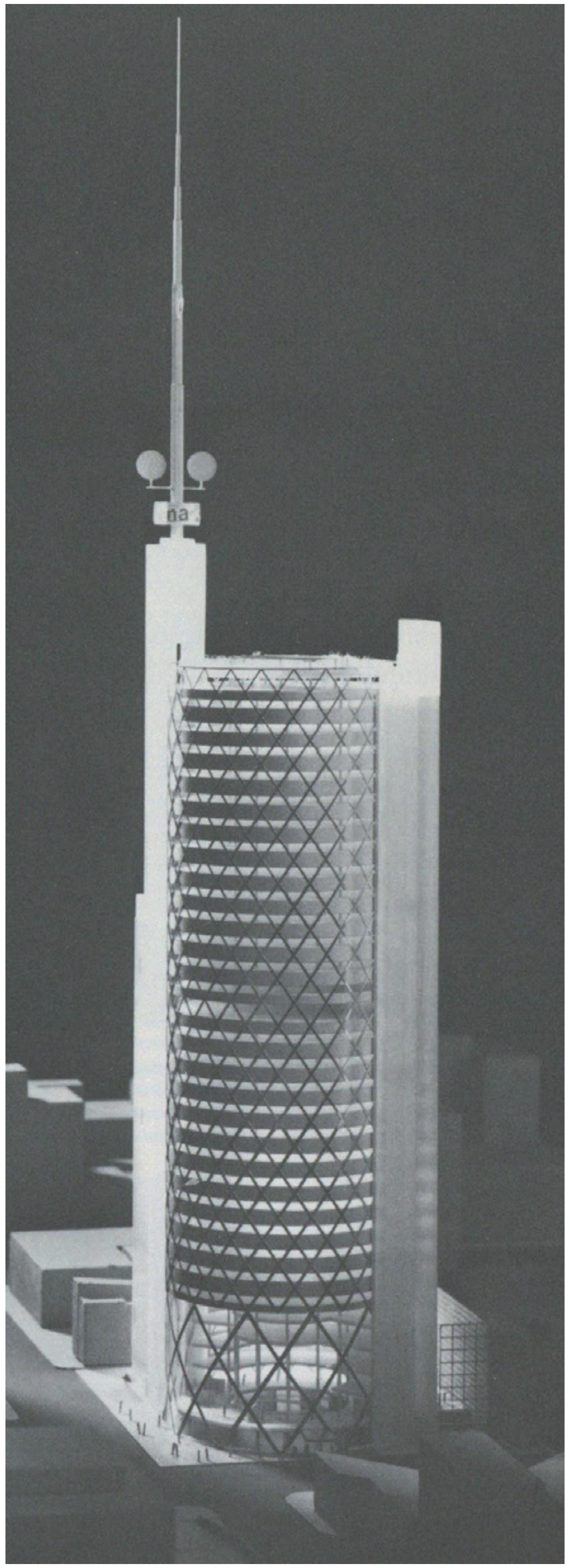
Skidmore, Owings & Merril, *John Hancock Center*, Chicago, Illinois, USA (1970)

Aerial view from the Oak Street Beach. Completed in 1970, 100 storeys, 340m tall. The huge influence on the design of skyscrapers guarantee this building an incredible prestige and fame.

Figure 04
(Next page, right)

Norman Foster, *competition entry for the Humana Headquarters*, Louisville, Kentucky, USA (1982)

One of the first highrise proposals to embody the diagrid system as a main supporting system.



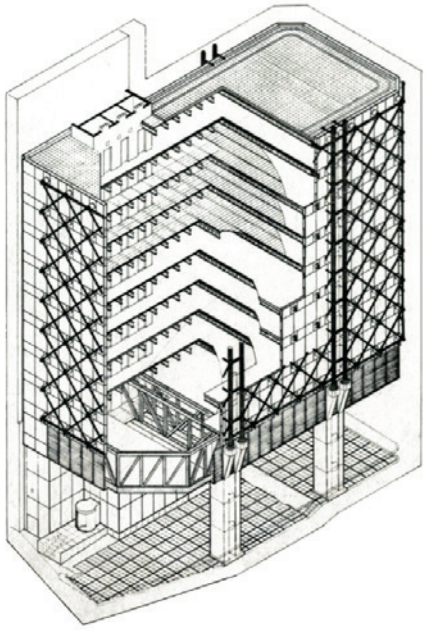
of the main influences on highrise buildings' structure and facade design. Typical example is the increasingly broad success of the *Diagrid-type*,[01] in which the diagonal members substitute all the conventional vertical columns. Compared to framed tubes, diagrid structures can minimise shear deformations by inducing axial tension-compression couples in the diagonal members. In addition, the strategy of placing diagonal members peripherally, instead of filling them in the building's core, consistently augment the effectiveness of their action. Another possibility offered by the concept of the diagrid is that of a concrete diagrid-like structure: the difference is that, while steel triangulated structures clearly express the support system of stacked diagonal braces, the possibilities of solutions given by reinforced concrete provide the designer with enhanced plastic expression in the design of the structural shells for skyscrapers. Finally, *Space Trusses* (three dimensional braced tubes, with diagonals spanning also on planes different from that of the facade itself) and *Superframes* (megacolumns at the corner of the building, with trusses every 15-20 storeys). In *Exoskeleton* highrise structures, the lateral resisting systems are placed at a distance from the envelope: while this approach improve the overall stiffness of the lateral system being applied (we may imagine of a braced tube or a diagrid structure set apart from the facade) some drawbacks have to be considered: thermal expansion/contraction of the fully exposed structure have to be considered and may cause many operational issues, as well as systematic thermal bridges between the structure and the interiors. On the other hand, less effort is required for fire proofing of the structure, and the enhanced possibility for an improved architectural expression. (Ali and Moon, 2007)

[01] First use of this typology dates back to the *IBM Building* in Pittsburgh, completed in 1963, supported by a steel lattice external frame, avoiding the need for vertical columns.

The possibility to think of architecture as turned upside down has been for architects and engineers in the second half of the XX century a massive design influence. The most dramatic example is the *Centre Georges Pompidou* in Paris and the design (1971-1977) by Renzo Piano, Richard Rogers and Gianfranco Franchini. Their proposal brought to international attention this high-tech approach: architecture has to follow the pace of technological innovation, and technology itself became the mean of expression for architects of this era. The advances of the *Beaubourg* would have never been possible without the counter-culture futurology of personalities such as that of Reyner Banham, or ideas such as those of the *non-architect* Cedric Price's *Fun Palace*. (Curtis, 1996) The British engineering firm Ove Arup & Partners took part in the development of the *Centre Pompidou*'s structural concept, with Peter Rice and Edmund Happold. Arup's practice, founded in 1946, based its early fortune in the field of design of industrial plants: the Englishman Ove Arup, founder of the corporation, recruited since the beginning talented architects. This led his firm to become internationally accredited for the holistic approach, merging together architecture, structure and service design, a blend of great influence for the new generation of high-tech architecture (Norman Foster, the same Richard Rogers and Renzo Piano, Grimshaw and Hopkins). (Powell, 2018)

The *Bush Lane House* (completed in 1977) is a remarkable example of this approach, as well as one of the first applications of a lattice (or diagrid) lateral support system that would completely avoid the need for interior vertical columns, allowing for a free-spanning 18m steel-concrete composite floor and a full open space. The choice of this unconventional structural system was also due to the peculiar conditions of the building site, a narrow piece of land, though interested by the ongoing construction of a new underground line. Severe restrictions emerged since the beginning, regarding the positioning of foundations, restricted to four individual spots. The resulting exposed steelwork was at odds with London's fire protection regulations, so it was prototyped a water-infill system that made the frame fire-resistant. Thermal deformations of the steel lattice had to be mindfully designed, and few contractors had experience with structural stainless steel, at least in the construction field (the casting of the braces was eventually carried out by a company involved in the manufacturing of steel elements for the dairy and brewing industry). (Brandenburger, 1976) Pushing the limits further imposed the engagement of a *technology transfer*. The dissemination of the diagrid-type gained growing relevance outside of the field of skyscrapers.

The idea of *technology transfer* suggests the process of dissemination of technologies from the field or institution they were supposed to belong, to a wider distribution of people and issues. This process has been practised for a long time by the high-tech architects, with their interest in other fields of technology, rather than solely for the field of architectural technology, and fairly often this approach resulted in a relevant innovation. The recent *NEO Bankside* development, designed by *Rogers, Stirk, Harbour+Partners* and completed in 2012, employs an external steel braced frame to support the facade, as well as to resist to the lateral loads of the wind. It does away with the necessity of inner lateral stiffening (i.e. shear walls, steel trusses), such as those typical of reinforced concrete *endoskeletons*, as a static support system of choice for vertical loads in this building, and it gives the facade architectural character, hereby a hierarchical order of relations between structure and construction. The braces meet every third floor with pinned nodes: the wind pressure is transferred to the diagrid outer system by the facade units (glazed or clad with oak panels) through these pinned nodes. A clear division of static and dynamic functions allowed also for some other major advantages: the construction process proceeded from the inside-out: once the concrete structure was completed, the prefabricated panels of the facade system have been applied without the need for expensive scaffolding, as it was already provided by the concrete frame. The external frame is prefabricated as well and mounted on site afterwards, finally putting the building in service conditions. The achieved construction rate has been of approximately one floor per week: a consistent improvement compared to the average pace, a considerable amount of money saved rather to improve quality of materials and spaces. (Rsh-p.com, 2019)



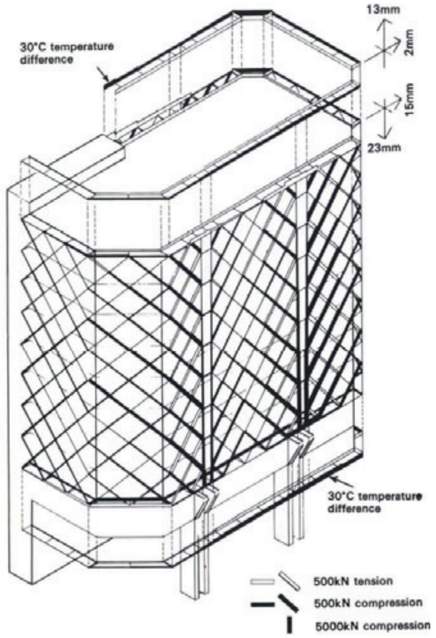


Figure 05 (Left)

Ove Arup & Partners, *Bush Lane House*, London, UK (1976)

Left: isometry of the building, showing the hierarchy division of the structural systems.

Right: lattice forces for maximum vertical loads and for a 30°C difference.

Figure 06 (Below)

Rogers, Stirk, Harbour+Partners, *NEO Bankside*, London, UK (2012)

Ongoing construction: the structural division allowed multiple processes to be completed at once, speeding up the whole process.

The skyscraper as an oscillator

Lateral actions on buildings have been for engineers a growing concern, while the strive for taller buildings grew over the last decades. For highrise, the main influence to be aware of, when considering lateral thrusts on towers, is the action of wind. This is a frequent, almost constant condition of stress applied to the towers, which act against lateral loads (at certain conditions) as an overall cantilever system fixed at the ground. Other lateral actions are those triggered by earthquakes, exceptional wind storms or, eventually, collisions and explosions. These factors have to be considered (and in fact are, as in the European structural design standards *Eurocode* and in all the countries' regulation) as exceptional load cases, that are, in particular for highrise buildings, often less decisive as wind actions in service conditions, since these actions have to be considered along with greater gravitational loads. The combination of gravitational loads and lateral actions is the true defining condition for the highrise buildings' structural design, in order to prevent effectively local and global buckling of the tower under the action of these two components. The relevant differences between gravitational and (most of) lateral loads are time and load application speed. The load application speed related to gravitational loads is really slow, in fact tending to zero. These actions can be considered as *static loads*, as they apply their thrust to buildings for an indefinite amount of time. Instead, what makes dynamic actions different from static loads, is their relevant application speed. Their intensity and action on buildings vary over time, determining dynamic load cycles over the structures. Other dynamic loads are for instance live loads: it is notable the influence of human induced vibrations, especially on lightweight footbridges and lightweight constructions.

The presence of *dynamic loads* implies the adoption of different analysis models for buildings and structures, the simplest of which is the *SDOF* (*Single Degree of Freedom*). Although buildings are structures with multiple degrees of freedom, it is possible to discretize the *MDOF* (*Multiple Degree of Freedom*) model by concentrating the mass of the building in its centre of gravity and considering overall mass and stiffness values that are representative for the entire system. When a single, simple dynamic load is applied, a buildings acts as an all in all harmonic oscillator. The dynamic equilibrium of this simple *SDOF* is expressed by the formula:

[1] $P(t) = m\ddot{u} + ku$

Where:

$P(t)$	*Applied dynamic load*
u	*Displacement*
$\ddot{u}$	*Accelleration*
k	*Stiffness*
m	*Mass*

If *P(t)* is the only force acting on the *SDOF* model, the simple oscillator undergoes a *Simple Harmonic Motion* (*SHM*). The oscillator opposes to the load *P(t)* thanks to its elasticity and inertia, respectively expressed as:

[2] $F_e = ku$ *Elastic force*

[3] $F_i = m\ddot{u}$ *Inertia*

Hence the displacement as a function of time might be expressed with the formula:

[4] $u(t) = A \sin(\omega t) + B \cos(\omega t)$

Where:
$\omega^2 = k / m$
A, B: *Boundary conditions:*
$A = \dot{u}_0 / \omega$ *initial speed*
$B = u_0$ *initial displacement*

According to these equations, it is possible to state the specific quantities of the harmonic oscillation:

[5] $T = 2\pi \, sqrt(m/k)$ *Fundamental or Natural period [s]*

[6] $R = sqrt[(\dot{u}_0 / \omega)^{2} + u_0]$ [m] *Amplitude [m]*

[7] $\omega = 2\pi f$ *Angular velocity [rad/s]*

[8] $f = 1 / T$ *Frequency [Hz]*

The only design parameters that is possible to tune, in order to alter the behaviour of an oscillator are mass and stiffness. A building with a higher overall mass will tend to have longer natural periods of vibration, while an increased stiffness will tend to increase the fundamental frequency, hence shortening the natural period of vibration. However, if mass is a property that is usually a consequence of the structural typology and material of choice, the main concern of structural engineering becomes, in this regard, the distribution of stiffness, as well as the overall stiffness of the cantilever-like behaviour of highrise buildings. The stiffness of a structure defines how much thrust is needed to displace a structure by a unitary amount: the higher the energy required, the higher the stiffness. However, if to higher stiffness values corresponds a shorter natural period of vibration, and although it can be advantageous in terms of deformation (at the same level of applied load, the displacements are lower), the strains in the structural elements will result in higher values. The downside of a *brittle structure* will be in fact its tendency to collapse under relatively small deformations. This type of brittle failure of a structure is, if possible, even more dangerous, since the bare deformations will create less warnings in the inhabitants before of the tragic collapse. A *ductile structure* on the other hand is able to undergo large deformations before the failure, and often allows for the creation of plastic hinges, that consist in a new, though altered, equilibrium.

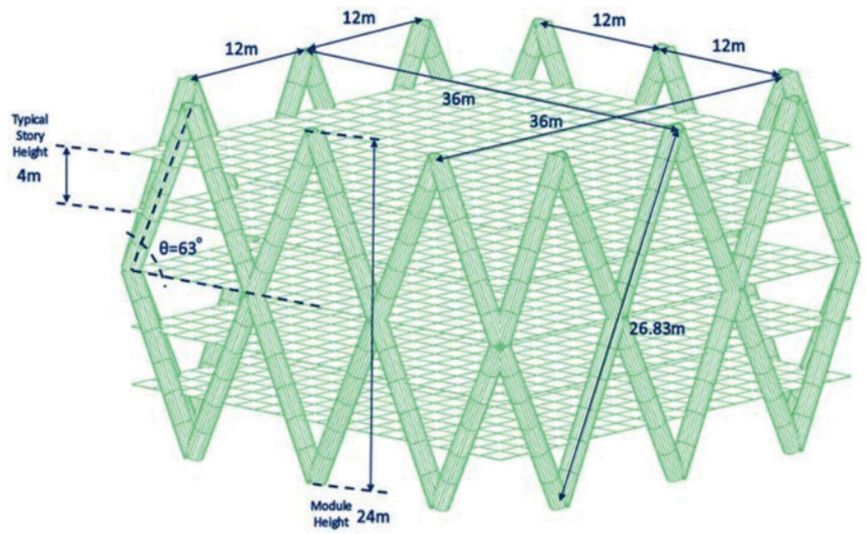
The recent development in form and structure of tall buildings has been determined, for the most, by the constant research for an always improved lateral stiffness against lateral dynamic loads, though a great innovation is expected to happen thanks to the recent advances in the field of building aerodynamics. (Ali and Moon, 2007)

Figure 07

Typical diagrid's geometry.

The definition of the angle of inclination of diagonal members is the main parameter in *diagrid-type*'s design.

Typical angles range between 60 and 70 degrees of inclination.



The improvement in lateral stiffness of the overall building, such that given by the adoption of an external structural system, allegedly causes a notable increase of the fundamental frequency of vibration, making it more difficult for the wind to engage a *lock-in* with the structure. (Moon, 2005) The structural evolution has evolved along with the research for a pertinent architectural expression. In traditional braced frames, the lateral resisting braces were usually placed at the core of towers, and they only served the structural performance of the building, while at the same time defining the canonical and static plan configuration (service and vertical connection shafts adjacent to the core, and the space between the core and envelope is either left free or divided in different properties, especially in residential towers). But with the emergence of exterior-braced tubular structures, the diagonal members, responsible for the lateral stiffness, became a decisive element in defining the architectural look of a skyscraper. Both in outrigger structures that, by means of transfers, connect the core to mega-columns at the perimeter of the building, and tubular typologies (such as the diagrid), the integrated design of facade and structure owes an ever-growing attention. The plan of the interiors is freed up of the most space demanding structural features (as braced or shear wall cores) responding also to the necessity for larger rentable spaces in dense urban contexts. (Moon, 2018) Furthermore, the convenience in terms of structural material usage is by no means of secondary importance. It is in this regard that most of the advances in the research on diagrid-like typologies are addressed. Diagonalized grid structures evolved as a highly flexible structural typology, with variations that apply not only to the use in highrise towers. The diagonals, most commonly organized in a diamond-lattice configuration, span over a canonical distance of 6 to 8 floors, where sprandel beams transfer the loads of the floors directly to the diagonals. The main advantage of the diagrid is that it often allows for an entire removal of vertical supports, unable to withstand lateral actions by means of axial stresses. (Broake, 2013)

Auxiliary damping in highrise buildings

The trend towards lightness, however, might cause some structural issues, such as structural vibrations induced by wind motion or service usage. In highrise buildings, serviceability of the structure has become the greater concern for structural engineers. Although materials are today available up to great levels of performance (structural steel is available with strengths from 170 to 690 MPa), the mechanical features of materials have less role in the control of vibrations and serviceability. The enhanced properties of today's materials, whilst improving structural lightness, determine paradoxically the onset of dynamic problems: only the use of *Auxiliary Damping Systems* can make up for these problems. (Ali and Moon, 2007)

Any oscillator, we know from the experience, when stimulated by a dynamic action (hence applied for a short amount of time) will not vibrate for an infinite amount of time without losing intensity, as the conservative equation [1] would suggest. It will rather loose kinetic energy over time, in fact coming back to the initial state of no movement. This happens because any oscillator, whether it is a simple *SDOF* or a very complex one, with multiple degrees of indeterminacy, will experience a dissipative force against the conservative forces of elasticity and inertia. This dissipative force is called *damping* and is for common structures the sum of the contribution of different types of damping, such as viscous or dry friction and hysteretic damping. The dynamic equilibrium of a *SDOF* becomes:

[9] $F_d = cu$ *Damping (dissipative force)*

Where:

u *Speed*

c *Damping coefficient*

[10] $P(t) = m\ddot{u} + cu + ku = 0$

[11] $u(t) = \rho_0 e^{-\zeta\omega t} \cos(\omega_n t - \phi_0)$

Where:

$\rho_0^{\,2} = u_0^{\,2} + [(u_0 + \zeta\omega u_0) / \omega_n]$

[12] $\ddot{u} + (c/m)u + (k/m)u = 0$

Where:

$(c/m) = 2\zeta\omega_n$

$(k/m) = \omega_n^{\,2}$

[13] $\omega_n = sqrt(m/k)$ *Natural frequency [Hz]*

[14] $\zeta = c / (2m\omega_n)$ *Damping ratio [-]*

The *damping ratio* is a dimensionless parameter, defining the rate at which oscillations decrease from one peak to the other, in other words the decay of kinetic energy of the system. The dimensionless definition of this parameter is derived as the ratio between the actual damping coefficient of a system and the critical damping coefficient. According to its characteristic values, it is possible to define specific behaviours of a damped system:

[15] $\zeta = c / c_c$

$\zeta = 0$ *Undamped system*

$\zeta < 1$ *Underdamped system*

$\zeta = 1$ *Critically damped system*

$\zeta > 1$ *Overdamped system*

The undamped system is the case of the simple *SDOF* oscillator, described above. [1] The mass would infinitely oscillate, continuously overshooting the initial state of static equilibrium, from one peak to the other. On the other hand, a value of the damping ratio bigger than 1 is typical of systems with very high values of dissipation: the overdamped oscillator, after the initial displacement, simply gets back to the initial position *u(0)*, without ever overshooting it: a critically damped system simply comes back in the shortest amount of time possible. Civil structures are all underdamped system: they experience, as a consequence of a dynamic solicitation, a series of peaks, gradually decaying until the initial state, in an amount of time that is strictly connected to their damping ratio. However, the definition of the intrinsic damping properties of a building is impossible at a decent level of accuracy, at least until the completion of the construction. Given this design issue, structural engineers' use of *auxiliary damping devices* allows to foresee the behaviour of their buildings. *ADD* can be divided in two main classes: active dampers, that rely on actuators and active control mechanisms to dissipate vibrations and need an energy source, and passive dampers, that have fixed properties and don't require energy in order to perform their function. While the former are the most effective because of their active and adaptable behaviour, the latter are by far more used in the construction industry, due to their affordability and reliability. (Ali and Moon, 2007)

Among passive damping systems, three possible kind of devices are known: *displacement dependant*, *velocity dependant* and *motion dependant*. Some other hybrid passive devices are *viscoelastic dampers* and *friction dampers*. For displacement dependant dampers the amount of energy dissipated is a function of the relative displacements at the opposite damper ends (maximum force corresponds to the maximum displacement of the system), while the dissipation of velocity dependant devices is directly proportional to the differential velocity at the elements' ends: their behaviour is usually out of phase with the building's displacement graph (since the maximum velocity happens while the system is not yet completely displaced). A typical example of velocity dependant devices are *Fluid-Viscous Dampers* (*FVD*): the basic mechanism consists in a piston immersed in a viscous fluid, actioned only when a motion is applied, while not participating to stiffness, nor to the equilibrium in static conditions. The greater the velocity applied, the greater the response: since any kind of spring restoring force is provided, the energy absorbed completely by the liquid and converted to heat. This consistently reduces the amount of energy being absorbed by the main structure's joints, up to high degree of dissipation. Furthermore, it is possible to design these devices to be very reliable over time: they are able to maintain their full functional performance after an earthquake event. *Viscoelastic Dampers* are a variant of the above mentioned, to which they add the behaviour of a spring, elastic reaction to displacements (being in fact a hybrid solution between velocity and displacement dependant solutions). On the other hand, devices that are based on the displacement curve of a building operate in hysteretic cyclic flexural/tensional yielding of particular materials (usually steel or alloys). *Shape Memory Alloys* (*SMA*) have the peculiar ability, known as superelastic behaviour, to recover their initial shape after large deformations. This is due to their ability to change their phase and back, through the heating (martensite) and load removal (austenite). It is however acknowledged that these kinds of devices may not recover their full functionality, and they may require replacements over time. *Friction Dampers* are hybrid devices, though their behaviour is similar to that of displacement dependant dampers: they dissipate energy through friction between metallic plates bolted together. They also share a similar non-linear behaviour, which inevitably, given that they can eventually stimulate higher modes of vibration, requires a non-linear analysis. However, they are able to dissipate a large amount of energy per motion cycle, although without a consistent restoring force they can't recover their initial state, unlike *SMA*s: they may cause higher life-cycle expenses for replacement or restoring.

The appropriate choice of a device depends in practice on the economic and technical boundary conditions of a project. These first two categories of dampers (known also as material-based dissipation systems) allow for the design of diffused damping strategies, where devices are placed at multiple location within the elements of the main structure, being most effective when placed where displacements or accelerations at their maximum. Different configurations are possible, the most common of which rely on devices placed on diagonal braces, though more complex and effective systems are available, both in term of dissipation performance and in term of space consumption. The last category of devices, motion dependant dampers, utilize instead the vibration of a secondary system, usually a mass or a liquid, tuned to the main structure: this approach, due to the complex design of the tuning and of the expensive implementation, is usually applied in very specific parts of an highrise building, at its top or in outriggers along the height. A *diffused damping* approach is therefore preferable for its easier behaviour and utilization: while working to directly reduce the energy in the primary structural system, it can act, if properly designed, on a wider spectrum of frequencies and modes of vibration, being suitable also as supplementary damping installations on existing buildings undergoing retrofit operations. (Lago et al., 2019) It is to expect that their employment and performance will rise in the next decades. Hence further experimental and practical applications of these devices will reduce the actual restrictions in terms of affordability and reliability, maintenance and consistency of the performance level over time.

Figure 08

WSP, *Torre Mayor*, Mexico City, Mexico

The 55 storey, 230m tall tower required advenced damping systems to satisfy the eventuality of severe earthquakes.

Diffused damping systems are placed along the crossings of each diamond-like grid of diagonals:

«[..] spread throughout the building so they act like the muscles on a skeleton.»
[Dr. Ahmad Rahimian, Director of Building Structures at WSP]

Learning from supertalls

Skyscrapers have lots to teach about the way technology holistically interplays with construction: intertwined to the high-tech development of tall buildings worldwide, the challenge of constructing these colossal buildings is constantly pushing limits forward. Industrialization, off-site or on-site prefabrication and, last but not least, automation of processes are integral part of the design of skyscrapers, in order to make highrise buildings financially sustainable. The rapid process of urbanization of cities in southern Asia, such as Singapore, teaches that skyscrapers constitute a different paradigm of urban developments, to which is connected also a challenge in terms of facility management: the arising of high costs for running and maintenance must be avoided with an adequate life-cycle design. Cost, quality and time are linked in supertalls construction by an unbreakable connection: with this in mind, the *Building and Construction Authority* (*BCA*) in Singapore publishes its regulations, among the most advanced in terms of highrise development. Rather than a prescriptive approach, whereby a description of the minimum requirement is often blamed to be an obstacle to innovation, they provide an example of a *performance-based regulation*, which specify the objectives to reach rather than the methodologies to follow. The objective is to produce a dense metropolitan habitat, though fully aware of the relation between constrains and resources, providing the right compromise of quantity and quality. The *BCA* aims to improve quality through high standards and innovative technologies, considering also that that affordable construction does not necessarily means poorly built: authority's task is to ensure that design and constructions comply with the required security and liveability standards, and in order to achieve this objective, to support industry's growth and innovation. (Chew Yit Lin, 2012)

The city-state of Singapore is the third denser country in the world and tenth by the number of skyscrapers taller than 150m.[02] About the 50% of the floor surface of these is occupied by offices, though a good 34% is left to the residential functions ("Singapore", 2019) Thanks to a strong intervention of the state in the real estate market, today four citizens out of five live in public housing complexes, most of which are hosted by highrise buildings. This estate of public housing is managed by the *Housing and Development Board* (*HBD*), with a trade-mark model of promotion and administration of their public housing assets. Highrise residential complexes are intended as vertical communities: they grant generous flat areas, while embodying by design vast common spaces to improve social interaction between the inhabitants. (Crabtree, 2017) The astonishing rise of Singapore (in a time frame of three decades, after the independence in 1959) can't be a matter of indifference: the ever present artificiality makes of this city state is a unique *ecology of the contemporary*: based on the idea of *tabula rasa*, on a reckless ideology of technological and political centralization as a standpoint at the gateway to globalization. (Koolhaas, 2010)

[02] 8.292 inhabitants per square kilometer. 89 skyscrapers are higher than 150m.

Figure 08

Ken Yeang, EDITT Tower, Singapore

Despite its controversies, the intense urban development of Singapore is the inevitable consequence of a global phenomenon: the exceptional pace of urbanisation worldwide, starting from the second half of the XX century, is destined to grow and with increased intensity. The phenomenon deals with the geopolitical actuality of the rural-to-urban migration and with the economical inescapable fact that urban land values will tend anywhere to go up. It is for these reasons that the skyscraper, as a mean for reducing the footprint of construction on urban land, deserves immediate and urgent attention from designers: though it is a reality that many issues of dense urban environment, for instance in terms of social and environmental sustainability, remain unsolved, it is a challenge for design to contribute to the research of solutions to these concerns. Often regarded as a destructive practice towards the environment, by favour of a shared ideal of low-rise communities that coexist with nature, the issue of urban intensification and its ecological aftermath seriously needs to be addressed, because it can consistently contribute to reduce the anti-ecological sparse disruption of ecosystems typical of low density settlements' layout. (Yeang, 1998) Ken Yeang's designs of skyscrapers propose some innovative typologies and technical solutions to integrate man and nature, where the highrise typology, as a humanity's best option for the development in dense urban environment, is the artefact that can allow this reconnection.

> *«[..]It is hoped here that by setting out the relationship between key design decisions and ecological issues, this work will help the designer of the skyscraper or other large building types to ask the right questions in the design process and make the appropriate informed decisions, which will then demand appropriate technical solutions.»*
> [Yeang, K. (1998). *The Green Skyscraper*. 1st ed. München: Prestel Verlag, pp. 15]

A "technological fix" may not be the solution to any environmental problem. However, necessity is what drives technical innovation: the design of the skyscrapers provides a plethora of at hand technologies and design solutions. It shows the intertwined work of many disciplines, pro-actively and holistically contributing to the demand for quantity and quality of the future artificial habitat. The evolutionary development of structural typologies, its dynamic interrelation with technology, architecture and science, never finds the least common between these disciplines, though it multiplies their possibility and creativity. The methodology proposed in this thesis is to be considered, according to what has been said here, the application of technologies and approaches typical of the design of skyscrapers in the operation of retrofit of existing residential constructions, given that the problem of highrise building's design, as here portrayed, is not totally unlike that presented by the crucial challenge of retrofitting existing ones for horizontal actions.

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Lightness in transformation

To master methodologies for retrofitting and restoring buildings in a light manner, while avoiding important interruptions in the services provided by the buildings themselves, is the feature of a culture that see transformation as a daily practice, and not as a difficult and invasive process.

> *«[..] mi piacerebbe che nel moderno riuscissimo ad adottare una capacità più chirurgica, una capacità di analizzare il problema e di trovarne la soluzione più adatta senza il bisogno che gli edifici debbano per forza essere tutti chiusi e si debbano fare delle operazioni troppo invasive.»*
> [Cucinella, M. (2018). *Un approccio innovativo per il recupero dell'architettura moderna.* In: A. Morelli and S. Moretti, *Il cantiere di restauro dell'architettura moderna. Teoria e prassi.* 1st ed. Firenze: Nardini Editore pp. 27]

Buildings need to adapt to the external transformations and boundary conditions. Changes occur also within the same building's organism: decay is the inevitable destiny of any artefact and indeed what to us appears still and fixed as our buildings, it is instead constantly evolving with its ecosystem. The lighter and less invasive the process of adjustment is, the higher the degree of adaptation the transformation achieves. Furthermore, the requirements and expectations in terms of performance are continuously rising. For, if the know-how of regenerating existing constructions will be able to produce appropriate methodologies for transforming the built environment, it will be possible to link the enhanced comfort and safety requirements with the topic of sustainability of the built environment, while taking into consideration the entire environmental and functional life-cycle of buildings and components.

As Mario Cucinella points out, two perspectives are shaping our approach towards the reuse of the recent architecture of the XX century: a *technical* one, defined by the contribution that technological innovation can provide to the necessity of reuse, and a *visionary* one, namely the way we relate with the existing heritage and which are the values we want to recognise and preserve. One of the most important aspects of our technical knowledge is the ability to conduct in depth analysis, digital simulations that not only allow us to see what used not to be visible with traditional and obsolete techniques (mostly based on direct observation of the artefact), rather it grants also the ability to do it with non-destructive methodologies that don't alter the original aspects of buildings, nor force an interruption in the usage of the buildings. But at the same time, in terms of vision of future perspectives, it is necessary to link this topic of an innovative reuse of existing buildings

with the issue of safety and energy. The recent seismic events recurred in our country have shown that the high degree of seismic risk on our territory is allegedly connected with chronic structural and energetic shortages, that all too often affect the Italian built environment. (Cucinella, 2018)

That two levels of intervention are possible when dealing with existing buildings, especially with those of the 20th century, for which there still lacks a practical shared knowledge of intervention, against the long tradition of restoration of traditional masonry architecture. This is due to the material differences introduced by the new technical means that led the rise of modern architecture. Traditional masonry construction is based on the concept of assembly, a concept that applies at different scales: single component (the brick), the building (assembly of different parts) and urban fabric (buildings are often organically grouped in clusters). The earthquake "selects" those weakest elements, eventually leading them to collapse. The assembly and discontinuity of masonry construction grant many advantages in terms of disassembling, hence in the seamless evolution and transformation of the built heritage, at the price of huge disadvantages in terms of strength in case of earthquakes. This paradigm is drastically overturned for reinforced concrete or steel buildings and infrastructures, that are in fact intended and designed as hyperstatic (statically indeterminate) structures, in which every member has several degrees of connection with the others. Hence a very different approach is needed when dealing with the modern heritage. The decay of concrete is profoundly different: when carbonatation attacks the reinforcements, the degradation of the material's mechanical properties is fast. The many degrees of static indetermination causes even a local damage to be relevant for the global stability, especially in case of earthquakes. Furthermore, where traditional repair of masonry allows an easy application of those canonical principles of renovation and repair, reversibility and compatibility, any intervention on modern buildings, built with modern techniques, will inevitably alter their original and pure aspect. One crucial difference is that modern architecture in not meant to develop the *patina* of historical buildings: modern architecture was designed to be perfect, linear, neat, free standing into an hypothesized infinite space. What used to confer so much authority to old buildings, is the same reason for the aspect of degradation and bad maintenance of modern architecture, with severe consequences for the durability of these artefacts. The action on the modern heritage is often a necessity: whereas the reinforcements of old concrete frame buildings do not correspond to the renewed security and stability requirements, the building needs to be updated. (Berlucchi, 2018)

> *«Il restauro del moderno non può più basarsi sulle ricette tramandatesi dai vecchi restauratori: le malte a calce realizzate in opera, magari con l'aggiunta di latte o caglio, non trovano più spazio. Il restauro passa dall'artigiano al tecnico di laboratorio, che deve formulare prodotti specifici [..]»*
> [Berlucchi, N. (2018). *Il restauro del moderno. Spunti e domande.* In: A. Morelli and S. Moretti, *Ivi.*, pp. 32]

A specialised maintenance becomes crucial for the care of the recent built heritage. Two methodological approaches, in particular, are recognisable in the contemporary culture of repair of the modern stock: the first implies the reinforcement of the main structure by adding material to the resistant sections, with modern high-performance materials (such as carbon fibres). This method, however, often requires a highly invasive operation, ultimately a lack of symbiosis with the former construction. The second approach consists in the introduction of newly designed shear resisting systems (gathered from the state of the art seismic structural design) external to the typical concrete-masonry frames typologies (commonly without effective lateral resistant systems). This is a practice of growing relevance: to add a so-called *exoskeleton*, that would guarantee both static and dynamic resilience to the primary structure. A "crutch" to the existing structure, acting as a passive dissipative dumper, or stiffening the former structure. For the restoration of the *Casa degli Artisti* (Milano), the great cultural interest of the building required an integrated architectural approach, that included also the addition of new contemporary volumes on top of the old artefact. Built in 1920 as one of the first reinforced concrete and iron constructions in Italy, this building, listed as cultural and historical heritage, imposed an integral conservation of the exterior original aspect: the exposed steel exoskeleton is therefore only visible in the interior of the building, juxtaposed to the original frame. It allowed in fact to protect the original composite structural floors, while at the same time providing both static and seismic up to date safety standards. All the additions are designed with declared and well recognisable contemporary materials and technologies. However, the applications of similar methodologies have to be studied in depth for not listed heritage as well. (Berlucchi, 2018)

The process of helping existing constructions with an external "crutch" implies the transfer of technologies from other fields, rather than from the traditional *modus operandi* of structural reinforcement. It is the case of a recent structural retrofit on the bridge over the river Reno (Poggio Renatico, Ferrara). A first-of-its-kind intervention on a steelwork viaduct of the late XIX century. The original steel trusses (three simply supported 50m long beams, spanning on two massive masonry pylons and abutments) were damaged after the 2012 earthquakes in Emilia Romagna. Although the damage was not severe enough to impose a limit to the railway traffic, the modified equilibrium consistently reduced the security levels of this crucial infrastructure and led to a strong increase of vibration. Pylons and abutments had to be reinforced: the foundations enlarged and provided with piles, the former masonry and loose rocks filled pylons, jacketed in a reinforced concrete layer. The main retrofit operation consisted of the addition of a new structural system, taking advantage of modern high-end technologies from long-span suspended bridges: brand new steel portal frames weigh on the jacketed pylons and abutments (the latter of which have been improved with additional concrete anchor blocks, lateral to the railway tracks): the

Figure 01
(Next page, above)

Studio Berlucchi, *Casa degli Artisti*, Milano, Italy (2011-2015)

Completed between 2011 and 2015 in two phases, a strategy adopted to minimize the interferance with the building's serviceability.

Figure 02
(Next page, below)

RFI, *Ponte ferroviario sul Reno*, Poggio Renatico (FE), Italy (2016)

A train crosses the bridge during retrofit's operations. Interference with the regular train traffic has been reduced to a minimum.

high strength steel cables support from below the existing truss decks. A cradle for the existing bridge: these beams have been placed temporarily first into position, to continue with the difficult operation of tensioning of the cables later on. The new system is provided with a monitoring system, that certified a reduction of 60% of deck's service deflections, and that will allow for the monitoring of excessive deformations. A strategy of adaptation for a crucial civil asset that avoided the demolition and reconstruction process: it was carried out with the least interference on the bridge's functionalities, and the redesign improved the overall degree of safety, while extending the useful life of this infrastructure. (Ceprini Costruzioni, 2017)

Exoskeleton structures for seismic retrofit

The analytical definition of an exoskeleton structure applied to the field of retrofitting existing constructions, designate an external dynamic system, (coupled to a primary one) whose mass is in principle not negligible and whose stiffness and damping properties can be varied by design, aimed at controlling the dynamic behaviour of the primary structure to which it is connected. The exoskeleton is a sort of "sacrificial appendage", called to absorb the majority of thrusts and deformations imposed by the primary structure, in the eventuality of a strong seismic event. In this light, the exoskeleton, as defined here, is differentiated from traditional studies on the connection of dynamic systems by means of dissipative devices, whose main focus is often oriented towards the global response of both structures. The focus of an exoskeleton's design, in regard to seismic reinforcement, is indeed to preserve and adapt the primary structure to the safety levels of up-to-date structural design codes. The simplified structural model can therefore do least by the consideration of the damping properties of the connection between the two systems, assuming a rigid connection between the two systems, hence maximising the transfer of thrusts to the secondary oscillator system. (Reggio et al., 2018) (Reggio et al., 2019)

The simplified model used to demonstrate the effectiveness of the external structure, as well as to study the best combination of design parameters for the exoskeleton (namely stiffness and mass ratios with the primary structure) consists in two SDOF viscoelastic oscillators. Given the equation of the damped harmonic motion of the two coupled masses M_1 and M_2 (the exoskeleton), consequence of a X_g acceleration:

[1] $M_1U_1'' + C_1U_1' + K_1U_1 = -M_1X_g'' + k\,(U_2-U_1)$

[2] $M_2U_2'' + C_2U_2' + K_2U_2 = -M_2X_g'' - k\,(U_2-U_1)$

Given the hypothesis of a rigid connection (limit case of a Hooke spring with the stiffness coefficient tending to infinite) between the two masses, since the displacements of the two masses tend to the same value, it is possible to consider the coupled motion of the overall system, expressed as:

[3] $(M_1+M_2)U_1'' + (C_1+C_2)U_1' + (K_1+K_2)U_1 = -(M_1+M_2)\,X_g''$

To state the problem in a more general manner, it is possible to rewrite this equation in non-dimensional terms,

[4] $(1+\mu)\ddot{u}_1 + (2\zeta_1 + 2\zeta_2\alpha\mu)\dot{u}_1 + (1+\alpha^2\mu)u = -(1+\mu)\ddot{x}$

Where:

$\mu = M_2 / M_1$ *Mass ratio*
$\alpha = \Omega_2 / \Omega_1$ *Uncoupled natural frequency ratio*
$\zeta_n = C_n / [2\,\Omega_n]$ *Uncoupled damping ratios*
$\Omega_n = sqrt(K_nM_n)$ *Uncoupled natural frequency*

according to the dimensionless variables of time and displacements:

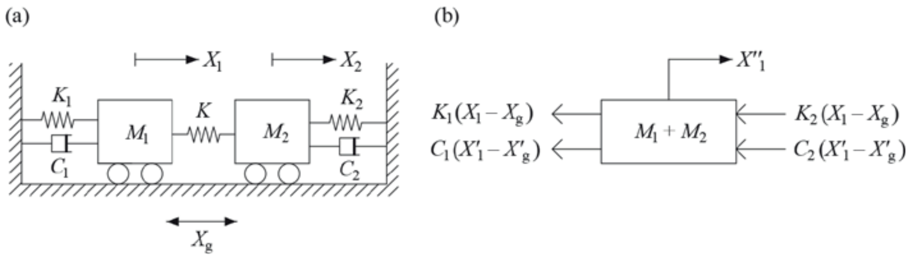


Figure 03

Coupled primary and secondary systems (Reggio et al., 2019)

Structural model (a) and free body diagram (b), with the hypothesis of a rigid connection.

[5] $\tau = \Omega_1 t$ *and* $u_1 = U_1/U^*$

Where:

$U^* = F^*/K_1$ *Characteristic value of displacement*
$F^* = M_1 g$ *Characteristic value of force*

These equations have been consequently used to evaluate the performance of a secondary oscillator according to the quantities of interest in seismic design, displacements (u_1) and accelerations ($\ddot{x}_1$) of the primary system. Motion $X_g(\tau)$ and displacement $u_1(\tau)$ are assumed to be harmonic with the ground motion's non-dimensional circular frequency ($\omega = \Omega / \Omega_1$): given the non-dimensional form used to express the problem, varying the frequency ratio (α), it is possible to plot the results, according the above mentioned performance evaluators, in *frequency response functions* (*FRF*):

[6] $H_{u1,xg}(\omega) = u_{10} / \ddot{x}_{g0}$ *System's relative displacement / base acceleration ratio*

[7] $H_{x1,xg}(\omega) = \ddot{x}_{10} / \ddot{x}_{g0}$ *System's absolute acceleration / base acceleration ratio*

The research project aims to verify the effectiveness and performance of different mass and stiffness (natural frequency) ratios of the primary and secondary structure. The sequent values are employed in the analysis, to plot the values of the *FRF*s against ω:

[8] $\mu = [0.001, 0.2]$
$\alpha = [0.1, 10]$
$\zeta_1 = 0.05, \zeta_2 = 0.05$

The definition of two response ratios allows to plot the results of the different combination of values against the response of the uncoupled system, thus generalizing the results with regard to the response of the primary system:

[9] $R_{u1} = {}_{max}\,|H_{u1\ddot{x}g}(\omega)|^C / {}_{max}\,|H_{u1\ddot{x}g}(\omega)|^U$

[10] $R_{\ddot{x}1} = {}_{max}\,|H_{u1\ddot{x}g}(\omega)|^C / {}_{max}\,|H_{u1\ddot{x}g}(\omega)|^U$

Where:

^{C} *Coupled system*
^{U} *Uncoupled system*

Another peculiar concern in the design of an exoskeleton structure would be the distribution of forces. The total of forces in the coupled system is the sum of the total contributions of springs and dampers, expressed also in non-dimensional form (under the same hypothesis above mentioned of harmonic motion of the system with ground's accelerations):

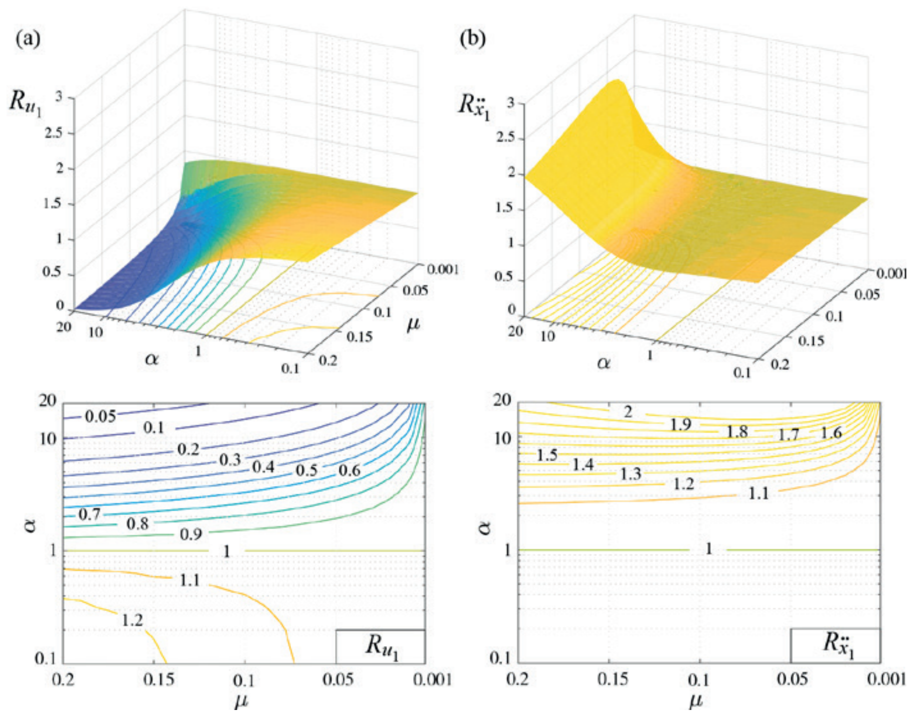


Figure 04

Surface and contour plots for response ratios of the coupled oscillators system (Reggio et al., 2019)

Response ratios R_{u1} for displacements (a) and R_{xg} for accellerations (b), combining different ratios of natural frequencies and mass.

[11] $F = (K_1 + K_2)\, U_1 + (C_1 + C_2)\, U_1'$

[12] $f(\tau) = (1 + \alpha^2\mu)u_{10}e^{i\omega\tau} + i\omega(2\zeta_1 + 2\zeta_2\alpha\mu)u_{10}e^{i\omega\tau} = f_0 e^{i\omega\tau}$

The *FRF* draws the ratio between the total of transmitted forces and the amplitude of ground's motion:

[13] $H_{f,\ddot{x}g}(\omega) = u_{10} / \ddot{x}_{g0}$

Which, due to the properties of the stiff constraint between the masses, can be distributed between the two oscillators as it follows:

[14] $H_{f1,\ddot{x}g}(\omega) = f_{10} / \ddot{x}_{g0}$

[15] $H_{f2,\ddot{x}g}(\omega) = f_{20} / \ddot{x}_{g0}$

Given that:

$f(\tau) = f_1(\tau) + f_2(\tau) = f_{10}e^{i\omega\tau} + f_{20}e^{i\omega\tau}$

Which, due to the properties of the stiff constraint between the masses, can be distributed between the two oscillators as it follows:

[16] $R_{f1} = {}_{max}\,|\, H_{f1,\ddot{x}g}(\omega)|^C / {}_{max}\,|\, H_{f1,\ddot{x}g}(\omega)|^U$

[17] $R_{f2} = {}_{max}\,|\, H_{f2,\ddot{x}g}(\omega)|^C / {}_{max}\,|\, H_{f1,\ddot{x}g}(\omega)|^U$

With:

$R_{u1}, R_{x1}, R_{f1}, R_{f2} < 1$ *Reduction of response*

$R_{u1}, R_{x1}, R_{f1}, R_{f2} = 1$ *Unaltered response*

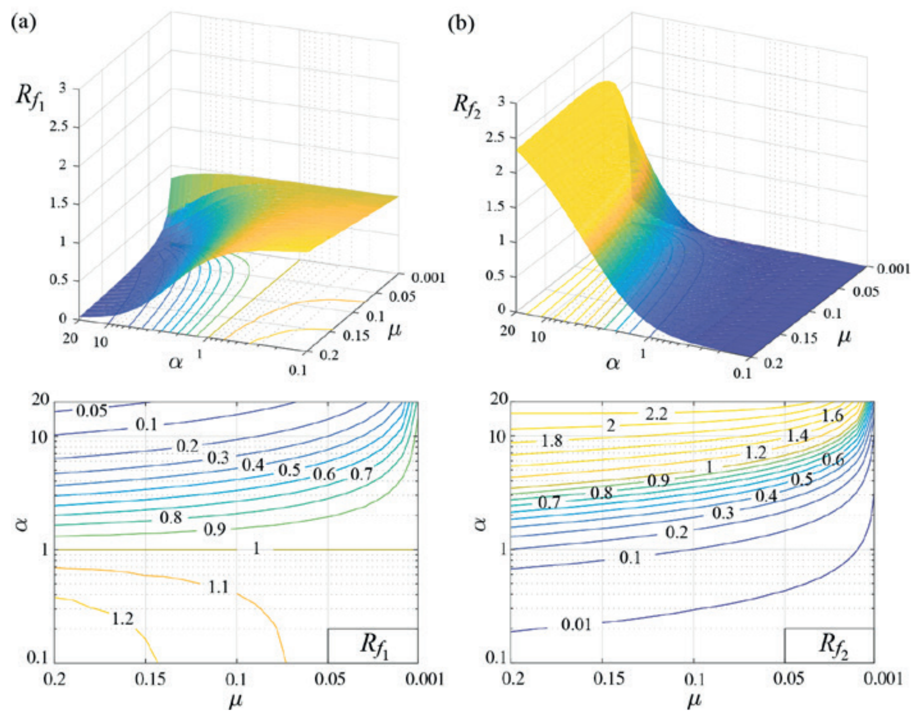
$R_{u1}, R_{x1}, R_{f1}, R_{f2} < 1$ *Enhancement of response*

Results show that response ratios for system's absolute displacements are inferior to one in a largest part of graphs, with peaks on higher values of

Figure 05

Surface and contour plots for response ratios of the coupled oscillators system (Reggio et al., 2019)

Response ratios R_{f1} (a) and R_{f2} (b), describing the distribution of forces through the primary and secondary systems, combining different ratios of natural frequencies and mass.



natural frequency ratios. Different results are shown by the response ratios in terms of accelerations: considerable amplifications are manifested in some parts of the graph, corresponding to greater values of natural frequency ratios, and almost independently from the values of mass ratios. In the design of an exoskeleton structure, a trade-off between displacements and acceleration have to be carefully considered. The plot of results for the response ratios of forces through the primary and secondary structure show ineluctably a consistent reduction of forces in the primary system, demonstrating the effectiveness of a stiff exoskeleton structure to absorb the majority of stresses induced by an earthquake. (Reggio et al., 2019)

Different results might be obtained by integrating the above mentioned model with viscoelastic connections, instead of the hypothesized rigid one. A viscoelastic connection (such as that of Kevin-Voigt model dampers) alters the distribution of forces between the two systems: it is made of the combination between a parallel linear spring (with stiffness *K*) and a viscous constant (*C*). The constitutive law for the amount of forces through the connection, for a model made of two SDOF oscillators of mass *M* and position *U*, is:

[18] $F = (U_2 - U_1)\, K + (U_2' - U_1')\, C$

[19] $f(\tau) = \beta_K(u_2 - u_1) + \beta_C(\dot{u}_2 - \dot{u}_1)$ *(in non-dimensional terms)*

Where:

$\beta_K = K / K_1$ *Non-dimensional stiffness of the spring component*

$\beta_C = 2\,\zeta_1 (C / C_1)$ *Non-dimensional coefficient of the damping component*

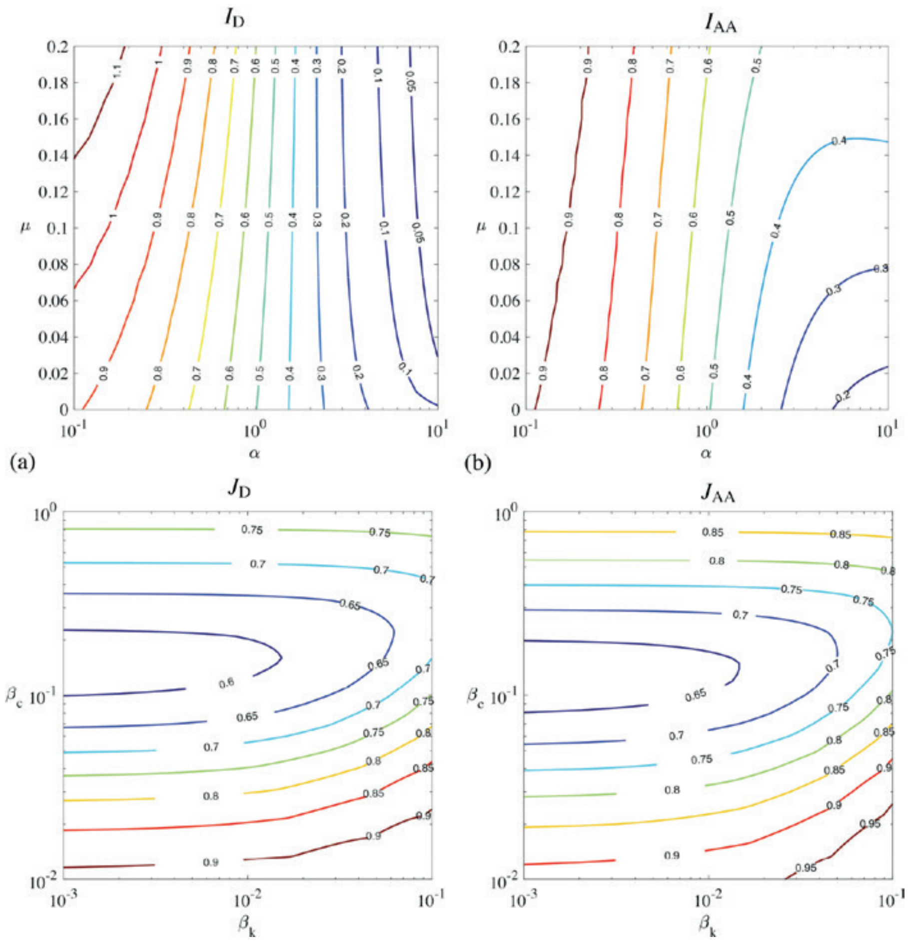


Figure 06

Contour plots for performance indices for the primary oscillator in rigid and viscous connection configurations (Reggio et al., 2018)

Performance indices (defined as the response ratios *R*) for displacements (I_D or J_D) (a) and accellerations (I_{AA} or J_{AA}) (b).

Above, the isocurves explain which combinations of *α* and μ parameters return the same performance index for a rigidly connected system.

Below, the performance indexes are plotted along with the values of β_K and β_C. Mass ratio and frequency ratio are fixed, for this plot, to values of, respectively, μ = 0.05 and *α* = 2.0

Also in case of viscoelastic connection, it is possible to design the properties of the connection to alter the performance response of the primary structure, ultimately providing another set of parameters, at hand for the structural designer in terms of performance control. **(Reggio et al., 2018)** It is however demonstrated that a secondary structure is able to alter sensibly the seismic behaviour, reducing overall displacements and relieving the primary structure to retrofit from a great amount of forces, even without employing a considerable mass. **(Reggio et al., 2019)**

Not of least importance, when introducing the concept of exoskeleton in the field of retrofitting existing constructions, is the choice of a proper structural typology and the evaluation of its performance when used for the purpose of adapting former reinforced concrete frames. As recent experimental dissertations have exposed, the emergence of structural typologies in the field of high rise construction (such as the diagrid type), typically intended to resist strong lateral and dynamic actions, offer to the purpose of an integrated retrofit the possibility to expand the vocabulary of possible interventions, while optimising both the structural response and the integrated architectural remodelling. **(Martelli, 2018)**

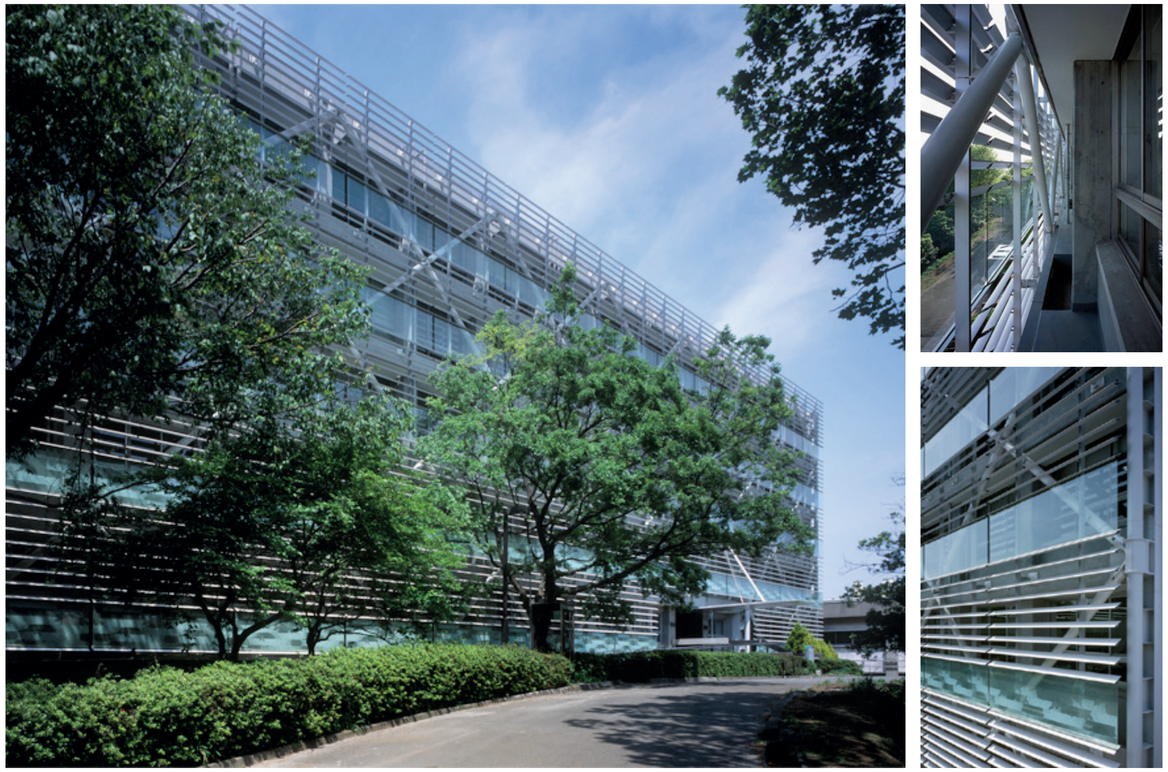
Figure 07

Studio Enarco, Teleios Engineering, *Palazzina Uffici e Servizi Magneti Marelli S.p.a.*, Crevalcore (BO) (2014)

[01] D.lgs. 14 gennaio 2008, in materia di "*Approvazione delle nuove «Norme tecniche per le costruzioni»*"

State of the art: external structures for seismic retrofit

The issue of an integrated structural and architectural retrofit of existing constructions has recently found an application in the redesign of the Magnete Morelli office building in Crevalcore (BO). Following the May 2012 Central Italy seismic swarm, the building showed severe structural damages: the staircase and external cladding panels had been damaged, as well as the majority of partition walls had been broken by the strong seismic-induced compression forces, as much as with some damages corresponding to the nodes between pillars and main girders. By no means these damages are a surprising eventuality: this building, completed in 1974, was not meant, by design, to cope with any significant lateral action. A series of twelve reinforced concrete pre-cast frames form the main structural support. The chosen engineering firm decided to let the main existing reinforced concrete frames to deal solely with the static forces, while designing instead the insertion of external shear trusses, correspondent to the existing structural grid of the industrial plant, to absorb the entirety of seismic dynamic loads. The commitment of both structural engineers, design team and clients allowed for a seismic retrofit up to the 100% of seismic functionality, as defined by the up-to-date Italian design code.[01] Completed in 2014, the redesign included an architectural refurbishment, both in the external cladding and in the attention to the detailing of the structural connections. The new facade strengthens the energetic performance of the whole building. **(Teleios, 2019)** Furthermore, with the amount of money saved against the eventuality of a complete reconstruction, further options have been considered to improve the environmental quality of the whole industrial site: planting of new trees, realization of rainwater tanks and new composting plant, solar thermal and photovoltaic systems on the roofs. **(Petricor Studio, 2013)**



A different approach can be achieved with the integration of diffused damping strategies: it is the concept of the *integrated facade* proposed by the *Koichi Yasuda Atelier* for the retrofit of the *Midorigaoka #1* building in the Tokyo Institute of Technology. The existing building, a mid-rise 6 storeys tall university facility built in 1966, therefore earlier than the reinforcement of the structural design code in 1981, can't rely on enough seismic proof features, such as proper hoop rebars in columns, making it extremely prone to severe shear failures in the eventuality of a strong earthquake, a condition fairly expectable given the Japanese high seismicity. To reduce this evident vulnerability, the longer sides of the facility are enveloped in a diamond-like lattice of external *buckling restrained braces* (*BRB*) that, besides their main function of high-performance dissipation of seismic energy of the concrete structure, offer also the possibility to integrate the seismic retrofit with the insertion of a new layered, high performance facade. The objective of the seismic retrofit is to avoid failure at any safety level: to cope with the great deformations, pillars of the first two storeys have been additionally reinforced by means of carbon fibre strips. Empirical laboratory tests showed that, with the combination of carbon fibre materials on selected nodes of the existing structure and external *BRBs*, it is expectable to achieve stable hysteretic cycles of structural response for deformations up to four times bigger as those of the original reinforced concrete frame. One of the main challenges had been the design of connections to the main structure: according to the structural analysis, these connections would

Figure 08
(Previous page)

Yasuda Atelier, *Tokyo Institute of Technology Midorigaoka #1*, Tokyo (Japan) (2006)

The new building's facade, integrating the external *BRBs* and the new layered skin (close up on the right).

Figure 09
(Right)

Karim Nader Studio, *Banque du Liban CMA*, Beirut (Lebanon) (2018)

Main elevation (left) and elevation on the courtyard of the former building (right).

have had to transfer horizontal forces as big as 2800 kN. Chemical anchor bolts have been drilled from the outside, all along the exterior side of the perimeter beams. Corresponding to the anchors, and taking advantage of the former pre-cast concrete eaves, H section steel beams with shear studs are inserted and connected to a short diaphragm like slab to rigidly bound the external lattice to the main structure. The gap between former and new beams is injected with mortar, to fill the hollow niche left by the connection. The *integrated facade* approach allowed for an integrated seismic and environmental improvement of the building (introducing a double skin and louvres for passive heat gain control) with the least interferences with the building's function: the intervention was completed within the time frame of a summer break from lectures. (Takeuchi et al., 2009)

The same intention, to save an old building from its ineluctable destiny of decay, inspired the recent redesign on the office high rise of the *Capital Market Authority* (*CMA*) in Beirut, designed in 1952 by Lucien Cavro and Antoine Tabet. Aiming to save this building, part of the extremely valuable modern heritage of the city centre, the design of an external black steel armour both consolidates the former building, adjusting it at the current seismic safety standards, and gives a new, contemporary image, embodying the values of strength and safety of a bank, together with the contemporary values of transparency and naturalness, granted by the new glazed surfaces and sparse greenery all over the elevations. The addition integrates security stairs and new terraces on the rear elevation. (Karim Nader Studio, 2018)

Knowledge-Based methodology

Given the contemporary, well established definition of seismic risk as:

[Seismic Risk] Risk = *Hazard x Vulnerability x Exposure*

While nothing can be done to alter the hazard of a particular context and very few can be done to modify the degree of exposure, it is instead an ever more relevant design topic to intervene on the seismic vulnerability of the built environment, in other words its proneness to experience collateral damages after an earthquake. In parallel, the forthcoming politics of development, oriented towards buildings' reuse and land use reduction, imply a renewed and growing attention towards the topic of the vulnerability of existing constructions. The matter of an adequate knowledge becomes crucial: a deep comprehension of the vulnerabilities of the building stock is necessary to achieve the required design intelligence, hence to reach a proper level of safety. The commitment towards the repair of existing infrastructures starts from an adequate project of knowledge: the study of the existing condition is it is in first place the contemporary, enhanced ability to collect historical and analytical data about existing artefacts to raise the issue of an integration of higher degrees of intelligence in the process of restoration.

Modern structural design codes increasingly took on the problem of the seismic vulnerability of existing buildings: the contemporary state of the art of national codes in Europe is based on the *Eurocodes*, promoted by the *European Commission* (*EC*) and developed by the *European Committee for Standardization* (*CEN*). (Eurocodes.jrc, 2019) Divided in ten sections, part eight is dedicated to the design of structures for earthquake resistance, including the assessment and retrofit of existing constructions.[02] The code introduces the concept of *Knowledge Levels* (*KL*): the choice of the analysis method is dependant from the degree of knowledge that is possible to achieve about the specific case study. Ranging from 1 to 3 (from worst to best), these levels depend on the degree of knowledge of the structural system's geometry, on the available amount of information about structural details (reinforcement for reinforced concrete frames, connection of steel members) and about materials' mechanical properties. An adequate *Knowledge Level* is to be assigned to each of these aspects, based on the reliability of original documentation and of structural codes at the time of construction (simulated design methodology), together with the degree of accuracy of on site inspections and testing; consequently, regarding the characterization of materials' mechanical properties during the structural analysis, the selected values are to be reduced by means of an appropriate *confidence factor* (*CF*). Although the reliability format adopted by this code can claim several advantages, in first place the simple yet effective distinction of the typical assessment process' uncertainties from those proper of the design process, there still exists a number of theoretical limitations to be addressed by the designer/assessor. (Bisch et al., 2012)

[02] EC 1998-3:2005 "*Eurocode 8: Design of structures for earthquake resistance. Part 3: Assessment and retrofitting of buildings.*"

Figure 10

Knowledge levels with corresponding methods of analysis and *confidence factors* (EC 1998-3:2005)

KNOWLEDGE LEVEL	GEOMETRY	DETAILS	MATERIALS	ANALYSIS	CF_{KLn}
KL1	From original construction drawings with sample visual survey or from full survey.	Simulated design in accordance with relevant practice and from limited in-situ inspection.	Default values (standard at time of construction) and from limited in-situ testing.	*Lateral Force* (*LF*) *Modal Response Spectrum* (*MRS*)	1.35
KL2	From original construction drawings with sample visual survey or from full survey.	From incomplete original detailed construction drawings with limited in-situ inspection or from extended in-situ inspection.	From original design specifications with limited in-situ testing or from extended in-situ testing.	*Lateral Force* (*LF*) *Modal Response Spectrum* (*MRS*) *Non-linear Static* (*Pushover*) *q-Factor Approach*	1.20
KL3	From original construction drawings with sample visual survey or from full survey.	From original detailed construction drawings with limited in-situ inspection or comprehensive in-situ inspection.	From original test reports with limited in-situ testing or from comprehensive in-situ testing.	*Lateral Force* (*LF*) *Modal Response Spectrum* (*MRS*) *Non-linear Static* (*Pushover*) *q-Factor Approach*	1.00

In this regard, the architecture of the XX century, especially that built after the World War II, can claim a great advantage on any of its predecessor: given the institution of city archives (to store the executive design and structural documentation including private developments) it is often possible to gather important documentation regarding the original conception of a building, about its design process and characterization of technological and structural components. However, a recurring issue, related to the improved availability of original design documentation, is the frequent lack of compliance of these document sources with the actual buildings they refer to: the inevitable decay of the building, the eventuality of subtle damages due to past seismic or exceptional events, the frequent mistakes, unauthorized constructions and subsequent modifications that occurred during the original building process. Consequently, the reconstruction of information coming from archival sources has to be carefully considered together with the empirical, on-site analysis of the case study: a preliminary survey of the building can reveal gross differences between the original drawings and the built object. However, many possible differences (for instance regarding the properties of materials and of reinforcements for concrete frames), are not for all to see at an indirect degree of observation. It will be afterwards essential to undertake more accurate survey operations, to get a better understanding of the exact state of conservation of the case study. (Gabrielli and Dell'Armi, 2018) On the one hand, the knowledge of existing structures can rely on improved abilities of empirical analysis: not only it is improved the degree of accuracy of these assessments, it is also the enhanced ability to conduct these studies without interfering with the material conditions and the everyday uses of the building to disclose the most promising results. The field of *Non-destructive Testing* (*NDT*) includes many techniques of precise measurement, aimed at reducing at a minimum the invasiveness of these investigations: a correct prescription of the methods to deploy within the survey of a building tries to weight the accuracy of indirect investigations (i.e. *Non-destructive Diagnostics*) with the outline given by archive sources, by general direct measurements and by destructive tests on materials and sections (used in few, selected parts of the building). (Morelli, 2018) The complexity of these operations demands for a concerned design of the process of acknowledgement, and confronts architectural design with the choice of a proper methodological approach: while a scientific method, based on a deductive-quantitative methodology in which the accuracy of its rigorous analysis is allegedly connected with the solidity of the input hypothesis, finds limitations right in the effective consistency of the initial assumptions (here contextualised, the accuracy of the archival and measurement's data), it is much more desirable for designers to rely on an inductive-qualitative methodological approach. The difference is that the latter is based on observation and experience, which are the key elements to filter and interpret the experimental data coming from direct and indirect document research and on-site measurements. Finally, the ability of analysis and interpretation of the designer comes into account, the missing link between the objectivity of data and the simplified reality of the structural model, by no means fixed in time, rather susceptible to incremental perfecting and modification. (Bozzetti, 2018)

Some intriguing perspectives, with regard to the issue of a perfected methodological approach of assessment of existing buildings' vulnerabilities, are being disclosed by the advances in data and information management. *Knowledge-Based Engineering* (*KBE*) depicts a wide range of knowledge intensive activities of engineering, design and manufacturing, where a big amount of input information is being used to solve complex problems. In traditional *KBE*, a great emphasis is placed on the role of technological tools (hardware and software able to gather, organize and analyse huge amounts of data) and the relation of these technologies with the canonical technologies of design, engineering and manufacturing, such as *CAD*, *CAE* and *CAM* software. It is however a widely appreciated feature of this approach the improvement also in regard to the re-use of design artefacts and of *Product Life-cycle Management*. Typical advantages of *Knowledge-Based Systems* (*KBS*) are standardized knowledge models, allowing easier integration and interdisciplinary, an easier and more efficient classification of information, allowing for reuse, maintenance, and extended automation. ("Knowledge-based engineering", 2019) For the building industry, major advantages of knowledge-based processes might consistently affect many recurring issues of maintenance. The management of buildings accounts for the largest part of their useful life, and maintenance (whether preventive or corrective) is indeed a highly case-specific activity. Furthermore, the activity of maintenance of the built environment traditionally involves many stakeholders and specific disciplines, making the availability of correct and up to date information a necessity to reduce costs and inefficiencies. *BIM* (*Building Information Modelling*) methodologies can overcome these problems in a comprehensive manner, by transforming the way that technical information is stored and shared among the many involved stakeholders. (Motawa and Almarshad, 2012) A necessary development, in this respect, framed as a typical knowledge management issue, is the creation of a taxonomy for maintenance: several attempts of standardized classification systems have already been proposed.[03] For, if the relevance of risk management to the *AEC* industry has already been underlined in the previous chapters, the role of knowledge management and *BIM* to facilitate the storage and communication of risk information and to enhance the accuracy of vulnerability assessment is crucial. Although, given the novelty of these concepts, a full integration of these fields is far from achieve, it is to expect a pressing need to support risk management and decision making throughout the entire life-cycle of buildings with appropriate and improved knowledge-based methodological approaches. (Zou et al., 2015)

Performance-Based methodology

Connected to the above mentioned definition of seismic risk, the design of structures for earthquake resistance is the typical application of a *Performance-Based Design* (PBD) approach. In fact, since the decisive variables (and possible combinations among them) for the seismic resistance of a building are many and often at odds between them, it is better, for modern design codes, to set the standards in terms of performance, rather than prescribing case-specific measures. Compared to the traditional prescriptive approach of past design codes, the approach has evolved towards a qualitative-performance one: according to the ever-changing boundary conditions and specific requests, freedom is left to the designer to choose the strategy that responds best to these expected levels of performance. The evaluation of the achieved level of performance is obtained through the use of standardized calculation techniques, capable of adapting to the different conditions, upon reaching an adequate level of knowledge of the boundary conditions and a weighted justification of the chosen qualitative objectives. (Muscio, 2010) Eurocodes embody this approach by introducing the concept of *Limit State Design*.[04] General requirements of structural design are defined in terms of structural resistance, serviceability and durability. The choice of adequate reliability requirements is to be made according to evaluations about the relevance of the infrastructure and in an economical way, allowing the structure to withstand all actions that are likely to occur during execution and useful life, and to meet specific serviceability and structural comfort criteria. This choice can't do less of an appropriate design of structures and detailing, a proper prescription of materials and the design of strict control procedures for the final execution.

[03] ISO 12006-2:2015 "*Building construction: Organization of information about construction works. Part 2: Framework for classification.*"

Proposal of a framework for a classification system of the built environment, regarding the complete life-cycle of artefacts (from construction to demolition). A set of recommended classes for building information models is identified, together with standardized sets of sub-systems.

[04] EC 1990:2002 + A1:2005 "*Eurocode: Basis of structural design.*"

The requirements in terms of durability impose the structure to be designed in order to maintain its level of performance above the intended thresholds, with regards to the environmental context and the expected maintenance operations. The *design working life* of the structure is directly dependant on the importance and implicit durability of the asset being designed: within this time frame, measured in years, the structure is expected to experience external actions. Following the principle of *LSD*, different performance requirements are set for *Ultimate Limit States* (*ULS*) and *Serviceability Limit States* (*SLS*): the first referring to the safety of people and of the structure itself, the latter to the comfort of its users, its appearance and functionality under normal and persistent conditions. To each limit state, a peculiar structural load model is assigned, with different combinations of actions and coefficients, to outline the related degree of performance. The same outline is indeed reported in the *LSD* procedure for seismic actions,[05] being *ULS* associated with failure and collapse of the structure capable of putting in danger the residents, and *SLS* considering the limitation of minor damages, though able of reducing the functionality of a building.

The recently updated Italian national structural design code[06] embodies the concept of *Limit State Design* and, broadly speaking, that of *PBD*, however already extensively covered by its former version of 2008. **(Cimellaro and Marasco, 2018)** The basic reliability requirements are expressed, as with the Eurocode, as structural resistance, serviceability and durability. The same outline is used for the definition of the limit states, divided in two main classes: ultimate and serviceability. Though, when it comes to the norms regarding structural resistance for seismic actions, the Italian code divides these classes in two further parts: *Operational Limit State* (*OLS*) and *Damage Limit State* (*DLS*), regarding the serviceability performance requirements, *Life safety Limit State* (*LSL*) and *Collapse prevention Limit State* (*CLS*) for the ultimate limit state structural evaluation. The definition of the different limit states is dependent on the exceeding probability P_{VR} in a given time frame V_R, in turn dependant on the initial choice regarding durability, and directly dependant on the importance of the structure.

[Reference Period] $V_R = V_N \cdot C_U$

Where:
V_N *: design life [years]*
C_U *: class of importance [-]*

For each limit state, and bounded exceeding probability, it is possible to calculate the return period for the design response spectrum, related to the limit state of choice and the reference period:

[Return Period] $T_R = V_R / ln(1-P_{VR})$

Where:
V_R *: reference period [years]*
P_{VR} *: exceeding probability [-]*

[05] EC 1998-1:2004 *"Eurocode 8: Design of structures for earthquake resistance. Part 1 : General rules, seismic actions and rules for buildings."*

[06] D.M. 17 gennaio 2018, in materia di *"Aggiornamento delle «Norme tecniche per le costruzioni»"*

Figure 11
(Table, above)

Input parameters for the definition of seismic actions: ***design life***, ***class of importance*** and ***exceeding probability*** of the four seismic limit states (NTC 2018)

Performance:	Temporary	Ordinary	Extraordinary
V_N	10	50	100

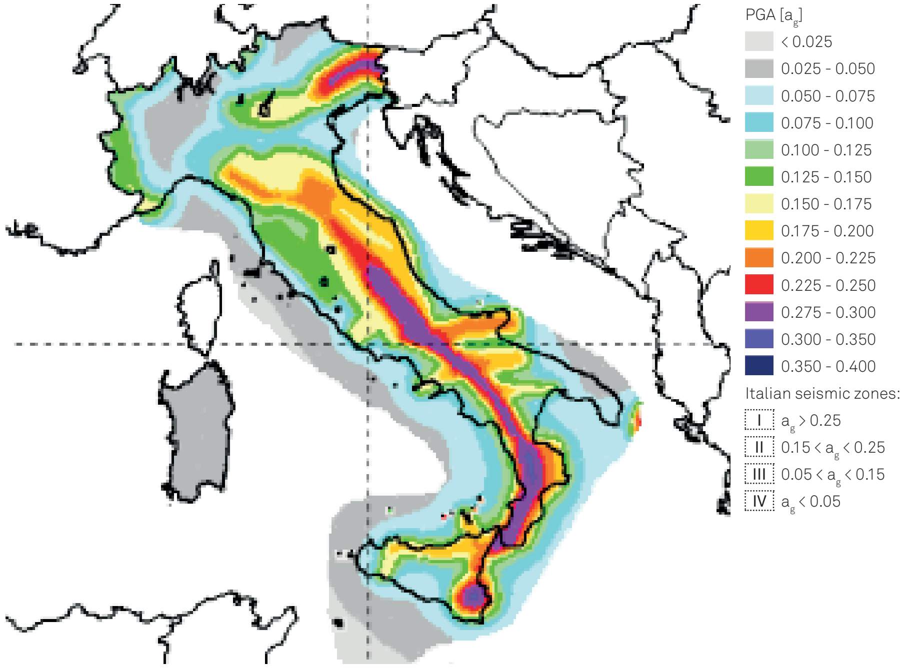
Class of importance:	I	II	III	IV
C_U	0.7	1.0	1.5	2.0

Limit States:	OLS	DLS	LSL	CLS
P_{VR}	81%	63%	10%	5%

Figure 12
(Right, below)

Map of the Italian seismic hazard (INGV, 2019)

Distribution of *Peak Ground Accelerations* and related colour scale. The reported values, used as well in the definition of four different seismic areas, are conventionally related to seismic events with a 10% exceeding probability in 50 years (with regard to the 50th percentile).



Structural modelling and analysis methods

The definition of seismic lateral actions, with regard to a chosen degree of performance inherent to the specific assessment, can follow a number of different methodologies. These, being specified in the current *Eurocode*, are indeed valid also with regard to the Italian context. It is possible to define two different approaches, static or dynamic, and two separate procedure categories (taking into account only a linear behaviour or including also the mechanical non-linearities). The choice of the analysis type does not depend on the required performance level, nor different methods of analysis are proposed for different kinds of operations (new constructions, retrofit or evaluation of existing buildings). It makes rather reference to the degree of complexity of the structural typology, and its representation's degree of accuracy. The first refers to the regularity in elevation of multi-storey frames, allowing for simpler, though less accurate, static linear analysis types (special reference to the regularity in plan which, if achieved, allows for a two-dimensional modelling of the building). The latter alluding instead to the accuracy in the definition of the structural model being used for the analysis. In this case, regarding the assessment of existing constructions, it is mandatory to refer to the knowledge level of the case study (as shown in Figure 10): to a lower degree of knowledge will allegedly correspond a simpler and less precise methodology. In addition, according to the structural material's characteristics, the *q-factor* defines the behaviour model supposed during the design or assessment process: as a function of this parameter, the degree of admitted ductility of the structure (brittle behaviour for q=1, growing ductility for q>1) influences also the choice of linear or non-linear types of analysis (the first being indicated for structures characterised by a brittle behaviour).

The *Lateral Force* (*LF*) method is a static-linear analysis which translates the inertial forces into an equivalent static action: the total seismic lateral force is divided into contributes for each specific storey and applied to the respective centre of masses (taking into account its deviation from the centre of geometry and the eventuality of an eccentricity of the actions). It is appropriate for structures whose response to the first modes of vibration in each of the main directions is consistently higher than those of the sequent ones, such that the contribution of these latter is negligible. It is the case of buildings in which the entirety of lateral resisting elements is regular in elevation, in other words without interruption from the foundations upwards, and with a constant, or gradually varying, degree of lateral stiffness at all the storeys. Buildings with setbacks are admitted, as long as these do not overcome some specific dimensions (function of the building's dimensions). Another important condition is that the fundamental period of vibration T is lower than $2.5T_C$ (maximum point of the response spectra).

The *Modal Response Spectrum* (*MRS*) dynamic linear analysis can be used for buildings that do not satisfy the conditions above mentioned with regard to the static linear analysis. The contribution of other modes, such as the torsional ones, becomes relevant: all modes with an effective modal mass participation greater than 5% are taken into account, until the total of the contributions reaches the 85th percentile. Once the modes have been determined, the combination of the seismic effects has to be evaluated, starting off from the response spectra obtained from the analysis.

Finally, non-linear analysis methods are used to calculate the structural response beyond the elastic range, at best considering also the eventuality of inelastic behaviours at large displacements, including strength and stress deterioration. These types of analysis require much more effort than linear analysis, not only in terms of calculations but also regarding the accuracy in the definition of the structural properties: with regard to existing buildings, for instance, they are in fact suitable only for a level of knowledge equal or higher than KL2. It is therefore much desirable to define some specific objectives: common use of such procedures is the analysis of unusual structural typologies, the assessment the buildings performance

according to very specific requirements of safety and to assess and design seismic retrofit solutions. **(Scuderi, 2016)**

The *Pushover* non-linear static analysis considers an equivalent SDOF oscillator, subject to ground motions represented by response spectra. Some assumptions have to be made: a single mode of vibration is considered, and it has to be constant during the analysis. A control point is set for the structure (usually at the top of the structure, where displacements are maximum), to allow its discretisation. The total of gravitational loads and of inertial forces F_b (or the total of shear forces at the bottom of the structure) is applied proportionally at each storey.

[Total base Force] $F_b = \gamma_{I,e} S_d(T_1) m\lambda$

Where:
$\gamma_{I,e}$*: importance factor*
$S_d(T_1)$*: ordinate of the response spectrum for the fundamental period* T_1
m: total mass of the structure
λ: correction factor (effective modal mass participation)

[Lateral force at storey *i*] $F_i = F_b[(m_i z_i) / (\Sigma^n_{i=1} m_i z_i)]$

Where:
n: total number of the storeys
m_i*: mass of storey i*
z_i*: distance of storey i from the ground*

These forces are augmented gradually, in order to increase the displacements of the control point (d_c), until the structure reaches a point of local or global collapse. The diagram of d_c is plotted against F_d is called capacity curve: it represents an evaluation of the overall structural response, allowing to evaluate inelastic deformations and plastic mechanisms or redundancy. The results of a non-linear static analysis can be used for both local (inter-storey drifts, strength demand in brittle components, ductility of dissipative ones) or global checks (global failure, margins of resistance to further gravitational loads). Since it allows to define analytically the point of global collapse of the structure (*LSC*), the pushover analysis could be useful in particular for the safety assessment of existing constructions. To each structural element, the proper characteristics have to be assigned in order to guarantee an accurate global behaviour: this stage constitutes a highly demanding design task, in particular when modelling existing constructions. Many design codes include however indications about the proper, experience-based values to assign to components of existing buildings. Finally, the degree to which the structural model's components fulfil the performance criteria is based on the demand to capacity ratio: a component is verified until the effects of an action are lower than its capacity. Two possible types of criteria are checked within non-linear analysis: deformations (usually decisive for ductile components' failure) and forces (regarding on the other hand the performance of brittle components).

Seismic retrofit and risk reduction

Regarding the issue of seismic risk mitigation, the proper definition of hazard is only one component of risk's equation. The persistence of important vulnerabilities of the building stock and the high level of exposure of the Italian territory constitutes a crucial challenge for retrofit operations on the existing heritage. For existing constructions, the extraordinary variety of typologies, structural materials and techniques of constructions allows for a vast set of solutions. For this reason, and coherently with the performance-based approach, the Italian code, also in the eventuality of the design of reinforcements for existing constructions,[07] does not prescribe a set of specific retrofit operations. It proposes instead a classification of the admitted interventions, their general description and foremost their objectives in term of performance in terms of structural safety: local or repair interventions, operations of improvement (partial retrofit) and full retrofit operations. The first category includes operations of repair or reinforcement regarding limited parts of the construction, thus not able of significantly improving the overall safety of the structure and that do not need static testing. Partial and full retrofit operations, instead, differ for the degree of safety achieved after their completion: the first allowing for a consistent, yet not complete improvement (with reference to the actual standards), the latter guaranteeing a complete adjustment of the existing building up to safety performance requirements specified by the contemporary structural design code for new constructions. The level of safety is defined as the ratio between structural capacity and demand, with regard to the only *ULS*. The evaluation of the performance level in terms of structural safety is, in the eventuality of structural interventions on existing buildings, a duty, whether the retrofit operation is partial or complete. As an operation of evaluation, in fact assessing the vulnerability of an existing asset, it ought to be based on a consistent knowledge based methodology and appropriate documentation, as highlighted above, capable of underlying the defining features of the case study: as a reflection of the state of the art at the time of construction, but also aware of the possible problems connected with defects of design or construction, and of possible damages or subtle, indirect actions or modifications occurred after the erection. It will be necessary for the designer of the retrofit intervention to specify the safety level of the building before and after the intervention.

With regard to seismic actions, the limit state of choice would be the *LSL*. The degree of safety against seismic actions is expressed by the ratio ζ_E between the maximum bearable seismic action and the design seismic action that would have to be considered for a new hypothetical construction on the same site. Partial retrofit operations imply the achievement of a ratio at least higher by 0.1 than that of the existing constructions, except for more important classes of buildings (such as schools or crucial public building or infrastructures) that need to achieve at least a ratio of 60% (without

[07] Treated in the 8th chapter of the NTC 2018

Figure 13 (Table, above)

Safety ratios for different types of interventions (NTC 2018)

Class of importance	I	II	III	IV
Partial Retrofit	$\zeta_{(E,r)} - \zeta_{(E,e)} >= 0.1$	$\zeta_{(E,r)} - \zeta_{(E,e)} >= 0.1$	$\zeta_{(E,r)} >= 0.6$	$\zeta_{(E,r)} >= 0.6$
Full Retrofit	$\zeta_{(E,r)} >= 1.0$	$\zeta_{(E,r)} >= 1.0$	$\zeta_{(E,r)} >= 1.0$	$\zeta_{(E,r)} >= 1.0$

Figure 14 (Table, below)

Classes of risk for constructions (D.M. 28 febbraio 2017, n.58)

Risk class:	A+	A	B	C	D	E	F	G
PAM [$\%_{CR}$]	[0, 0.5]	(0.5, 1.0]	(1.0, 1.5]	(1.5, 2.5]	(2.5, 3.5]	(3.5, 4.5]	(4.5, 7.5]	>= 7.5
IS-V [%]	> 100	(80, 100]	(60, 80]	(45, 60]	(30, 45]	(15, 30]	<= 15	

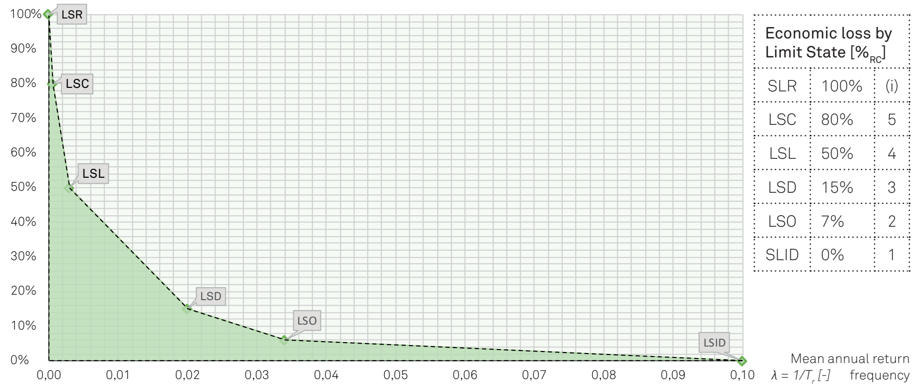


Figure 15 (Graph, right)

Trend of expected economical loss (D.M. 28 febbraio 2017, n. 58)

Direct economical losses as a percentage of reconstruction costs, against mean annual return frequency, for a new construction with V_N =50 years, II class of importance.

[08] D.M. 28 febbraio 2017, n. 58, in materia di "*Linee guida per la classificazione del rischio sismico delle costruzioni nonché le modalità per l'attestazione, da parte di professionisti abilitati, dell'efficacia degli interventi effettuati.*"

prejudice of the above mentioned condition). Full retrofit, instead, obviously require to achieve a degree of safety of at least 100%: except for change of functions that do imply augments of global vertical loads up to the 10% of the original ones (allowing a reduced final ratio of 80%), it is the case of addition of additional storeys, of enlargements, by means of secondary structures that significantly alter the response of the main structure, and in general, interventions that would change the original structural system and configuration of the existing building.

Following the shocking events of the Central Italy earthquakes and their tragic consequences in terms of casualties and economic losses to both public and private assets, it has been recently introduced a new classification standard for the vulnerability of existing constructions,[08] based on eight standardized classes of risk (A+ to G, from best to worst). These classes are specified separately for two different types of reference parameters: the average annual loss (*PAM*, *Perdita Annuale Media*) and the safety index (*IS-V*, *Indice di Rischio*), the first devising the mean annual economic losses connected to a building, expressed as a percentage of the reconstruction costs (*CR*, *Costo di Ricostruzione*). Two different methods for the assessment are proposed: conventional and simplified, the latter suitable for mostly masonry and traditional buildings, as an expeditious procedure for these types of structure or for preliminary evaluations. For the rest of typologies, the first method is required. Firstly, the full methodology requires the definition of the return period and of the mean annual return frequency (its inverse function) relative to each of the four limit states (or, alternatively, for the only *LSL* and *LSD*).

[Relative return period] $T_{r,C} = T_{r,D} (PGA_C/PGA_D)^{\eta}$

Where:
$T_{r,D}$: design return period [years]
η = 1/0.41
PGA_C : peak ground accelerations (construction)
PGA_D : peak ground accelerations (design code)

Two further limit states are introduced to the four of the NTC code, as boundary conditions for the economic losses' function: the limit state of initial damage (*SLID*, *stato limite di inizio del danno*) and of reconstruction (*SLR*, *stato limite di ricostruzione*). The first represents an economical loss tending to zero, conventionally associated with a $T_{r,C}$ of ten years (λ=0.1), the second the maximum acceptable structural damage (100% of reconstruction costs). Finally, an economic loss is associated to the other limit states: the lines connecting the different λ values of the limit states are a discretisation of the direct economic losses connected to the different limit states. The lower the area underneath this curve, the better the class of risk of the construction being evaluated.

[PAM] $\Sigma^{5}_{i=2} [\lambda(SL_i)-\lambda(SL_{i-1})]*[CR_{\%}(SL_i)+ CR_{\%}(SL_{i-1})]/2 + \lambda(SLC)*CR_{\%}(SLR)$

Where:
i: generic index for the limit state (Fig. 15)
$CR_{\%}(SLR)$ = 100%

The obtained value needs to be confronted with the ranges specific for each risk's class (Fig. 14). Furthermore, the designer must evaluate also the *IS-V* parameter, defined as:

[IS-V] $PGA_{C(LSL)}/PGA_{D(LSL)}$

Where:
$PGA_{C(LSL)}$: peak ground accelerations (construction) for LSL
$PGA_{C(LSL)}$: peak ground accelerations (construction) for LSL

Again, the result of this evaluation is to be compared with those given by the guidelines (Fig. 14). Finally, the correct risk class of the building being evaluated will be the lower among the two, to the advantage of safety.

Within the broader context of risk mitigation strategies, the advantage of a standardised methodology, providing a simple and graphical explanation of the seismic risk degree of a construction, can return considerable benefits in terms of communication of risk and its relevance for the inhabitants. Contextually, a transparent ans simple communication of risk is the first measure to undertake, in order to reduce the ambiguities and emotionality that often affect private homeowners when considering the option of a seismic retrofit of their dwelling. These social aspects, connected to the rise of "nudge" policies (such as the private insurance market on homes, connected to the evaluation of risk and vulnerabilities and governmental tax credits), are thought to ignite the development of a prolific retrofitting market of the existing residential stock. (Fujimi and Tatano, 2013)

Figure 16
(Table, above)

Recap of the *Sisma Bonus* policy (2017-2021)

Above: IRPEF/IRES benefits for seismic retrofits of MFH

Centre: IRPEF/IRES benefits for combined seismic/energy retrofits of MFH

Below: benefits for single dwellings purchases, after retrofit or reconstruction

Multi family buildings	Deduction [%]	Maximum amount of the expenses [€]	Deduction's breakdown	Interested stock	
				Zone	Operations
Building renovation	55%	96.000,00 €	5/10 years	I II III	Seismic retrofit
1 risk class	75%		5 years		
2 risks class (or more)	85%				

Multi family buildings	Deduction [%]	Maximum amount of the expenses [€]	Deduction's breakdown	Interested stock	
				Zone	Building use
1 risk class	80%	136.000,00 €	10 years	I II III	Seismic + energy retrofit
2 risks class (or more)	85%				

Dwelling purchase	Deduction [%]	Maximum purchase amount [€]	Deduction's breakdown	Interested stock	
				Zone	Operations:
1 risk class	75%	96.000,00 €	5 years	I II III	Reconstruction Retrofit
2 risks class (or more)	85%				

Seismic retrofit policies: the Italian context

The introduction of a seismic risk reduction policy coincides in Italy with the creation of the so-called *Sisma Bonus*,[08] a tax credit policy aimed at promoting the enterprise of seismic retrofit interventions within the private real estate market. Homeowners who decide to undertake retrofit measures to improve the seismic performance of their dwellings have access to a consistent "discount" (credit) on their annual income tax. While a tax credit for building renovation had long been present in the tax regulations,[09] with the new program the amount of deductible costs arose from 36% to 50% (and the maximum expense from 46.000€ to 96.000€), while the normal payment plan (10 yearly instalments) had been reduced to 5 years.[10]

The 2016 budget law introduced the second season of the *Sisma Bonus*, a three years plan of improved credits for seismic retrofit on housing and productive buildings on the national territory. Planned until January 2021, the *Bonus* has been confirmed and improved with further measures. In first place, the tax credit is made available also in the seismic zone III and the audience of possible annuitant is enlarged, from individuals (IRPEF taxpayers), to other types of entities (IRES taxpayers), such as IACP (*Istituti Autonomi Case Popolari*, Italian bodies for the development and management of the public housing stock), entities with the same social purposes, housing cooperatives and the various forms of undivided property. The budget is considerably enhanced: being understood that 50% of the entirety of assessment, design and construction expenses are deductible, up to a maximum of 96.000€, and connected to the introduction of the risk class methodology, the deductible sum is brought to 70% or 80%, respectively for improvements of 1 or 2 classes.

[08] D.L. 4 giugno 2013, n. 63, in materia di "*Disposizioni urgenti per il recepimento della Direttiva 2010/31/ UE del Parlamento europeo e del Consiglio del 19 maggio 2010, sulla prestazione energetica nell'edilizia per la definizione delle procedure d'infrazione avviate dalla Commissione europea, nonchè altre disposizioni in materia di coesione sociale.*"

[09] Art. 16bis in: D.P.R. 22 dicembre 1986, n. 917, in materia di "*Approvazione del testo unico delle imposte sui redditi.*"

[10] L. 11 dicembre 2016, n. 232, in materia di "*Bilancio di previsione dello Stato per l'anno finanziario 2017 e bilancio pluriennale per il triennio 2017-2019.*"

Particular attention has been addressed to the issues correlated with multi-family housing buildings, which manifested more difficulties being included in seismic retrofit campaigns, whether for the problems related to collective decisions and the willingness to pay of the inhabitants: besides the higher deduction rates, it has been given the possibility to sell the amount of cumulated credit, in order to considerably reduce the amount of initial expenses (up to the annulment) for the homeowner. Right in this direction, a new measure, introduced in 2019,[11] provides to the possibility for the customer of choosing, rather than the normal tax credit, an immediate contribution (in the form of a discount on the total amount of costs), anticipated by the contractor which will than earn his credit according to the normal procedures of payment. The return of the total amount of credit is however bounded at the above mentioned maximum amount of expenses: further interventions on the same artefact within the years of the specific bonus policy will not allow to additional credits. Additionally, it is not possible to access different modalities of payment rather than those specified by this measure, if not considering the traditional tax credit for building renovation projects, divided in 10 installations (augmented to 50%).

Finally, the 2017-2021 policy additionally provides benefits for retrofitted or rebuilt dwellings purchases, and an improved tax credit policy in case of combined seismic and retrofit interventions on multi family housing complexes: this latter consideres a maximum amount of expenses worth 136.000€ (for each unit) and a tax credit of 80% or 85% of this amount, that will be divided into 10 (yearly) installaments. Again, it will be possible to access to this bonus with two modalities: the normal tax credit, or the immediate discount (credit assignement to the contractor of the retrofit project). (Agenzia delle Entrate, 2019)

[11] D.L. 30 aprile 2019, n. 34, in materia di "*Misure urgenti di crescita economica e per la risoluzione di specifiche situazioni di crisi.*"

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Deep energy retrofit of existing constructions

The term *Deep Energy Retrofit* (often shortened DER) describes a recent construction approach aimed at introducing new technologies, materials and functionalities to existing buildings, preferring the operation of regeneration rather than that of reconstruction, as a socially, economically and environmentally acceptable construction approach. The deep character that is often associated to the energy retrofit approach is connected to the aim of making the retrofit a highly effective urban renewal practice: it implies that the combination of new additions to the old building will strongly influence its impact on the environment. When considering energy retrofit operations, the aim is that to reduce the building's operative energy demand by introducing state of the art, breakthrough components able to cut consumptions of these up to the levels of a corresponding new construction, responding to up to date standards. (Baeli, 2013)

Typically, renovations do not address the challenges highlighted by the changing climate, the shortage of resources and the rising costs of fuel. In this regard, the operation on deep retrofit can lead to a more effective approach, since it is possible to refer to real conditions, rather than to hypothetical values for new developments, with measurements coming from the experience and empirical measurement of the existing building. In addition, deep energy retrofit is committed at improving and aligning existing assets to the values and expectations of contemporary times, not only in terms of environmental impact, rather also in terms of comfort for the inhabitants. It is in fact in the holistic conception of the existing building's overall renewal that lies the difference with conventional retrofit operations, which include simple and fast operations on single building components (for instance, windows, lighting or HVAC equipment). Although being doubtless economically more feasible, these types of intervention often miss the opportunity of achieving true and consistent improvements in the environmental and comfort performance of existing buildings. At the same time, despite being more demanding in economical and design terms, deep retrofit operations might lead to much higher benefits, by virtue of their holistic and inclusive commitment. (c&h architects, 2020) This aspect itself clears up the distinction between the two dramatically different approaches, even if oriented to the same objective. It is also around the careful evaluation of impacts and maximisation of benefits, that the economic, environmental and social sustainability of building's renewal through deep retrofit operations ought to be evaluated.

[01] Data retrieved from: *Indagine sui consumi energetici delle famiglie* (2013) Istat

The methodology to be followed within the design process can be divided in two stages: the pre-planning phase and the planning phase itself. The first accounts as main objectives the clear definition of project needs, opportunities and goals. In some cases, it will be necessary (or strongly desirable) to consider the final user's needs, including their experience in the use of the spaces and functions being retrofitted. The knowledge of the existing asset is fundamental: direct inspection and energy audit methodologies have to be conducted carefully, in order to guarantee an adequate modelling and analysis of the existing building's physical behaviour. An important stage is the detection of possible health and safety issues, involved by the decay of outdated equipment or by issues regarding the air quality, the lack of daylight or noise pollution (to mention a few). Another important aspect to be carefully evaluated in this stage is the eventuality of performance metrics methodologies. While the access to users' data and experience is a valuable source of information about the existing building, the accuracy of these information is often debatable: connected to this typical knowledge issues, it is often preferred to set the performance requirements as post-retrofit absolute objectives, rather than as per cent reduction targets. At the same time, it is also questionable the effectiveness of traditional metrics methodologies to assess the overall performance improvement of buildings: for this reason, a whole house assessment is to be preferred to the typical floor area normalisation. Also, the careful distinction between site energy and source energy (and often its translation in equivalent carbon dioxide emissions) might allow for an adequate definition of project targets. Coming to the planning phase, the design of deep energy retrofit interventions respond to a complexity all in all equal, if not bigger, than that of a new construction. The integration and coordination of different technological systems is the main challenge here: to keep an eye on the gradual evolution of the project in relation to the targets defined in the first stage, by means of analysis models and design simulations of the physical characteristics of the building, though with great awareness of the limitations and simplifications. Furthermore, great attention must be brought on the construction process: in first place, since the operation of deep, integrated retrofits implies some peculiar and highly specific methodologies. Another recurrent issue is the frequent discovery of anomalies and defects of the existing artefacts, compared with the design and construction documentation. Finally, integral part of the design for deep retrofit is the post-occupancy evaluation phase: the testing of the final, effective results achieved by the intervention is crucial for a gradual tuning and adaptation of the building's behaviour to the users' needs. Furthermore, it might provide a sort of knowledge database, experience based, about the design for deep retrofit and its effectiveness. (Less and Walker, 2015)

The most energy demanding task of a building is by far space heating and cooling. Space heating, in particular, accounts in average for up to the 70% of the total energy consumption of Italian families.[01] Consequently, a deep

Figure 01

Mario Cucinella Architects, *Former postal office via Bergognone 53*, Milano (Italy) (2004)

Architectural and energy renewal of a complex of former office buildings. View of the southern elevation, clad with a contemporary, fully glazed double skin

retrofit should primarily address the system and components regarding this activity, that is to say the building's envelope and HVAC systems. With regard to the first, the aim is to enhance the ability of the construction's skin to retain heat in cold winter months and to maximise the contribution of solar heat gains, though with great attention at their reduction in the warm seasons. Approaching the envelope is indeed the starting point of any deep retrofit intervention, since it allows to reach the proper degree of performance (in terms of thermal resistance and air tightness), necessary for any further intervention on the system of thermal control appliances. (Baeli, 2013)

In addition, a different or complementary strategy might regard the introduction of renewable energy sources for on site production of energy: whilst this approach does not necessarily imply an improvement in the performance of building components, it surely contributes to reduce the primary energy demand of non-renewable, thus reducing the environmental impact of the building's life cycle. However, the combination of these complementary approaches might allow to turn existing, energy-hungry buildings of the past century into up to date nZEB (nearly Zero Energy Buildings),[02] with dramatic improvements in terms of environmental impact and benefits for the life and comfort of the inhabitants. The introduction of renewable energy sources is, furthermore, is a necessary step (yet, not sufficient alone) to allow for the ambitious objective of zero-carbon cities.

[02] Term introduced by the so called *Energy Performance of Buildings Directive* (EPBD): Directive 2010/31/EU of the European Parliament and of the Council (May 19th, 2010) on the "*Energy performance of buildings*"

Exoskeleton structures for whole life energy savings

As it has been mentioned above, the purpose of exoskeleton structures for retrofitting existing constructions goes far beyond the only structural reinforcement: the proposal of an update of the environmental performance of the envelope is necessary to make these interventions sustainable and marketable. The design complexity of the task lies in the interdisciplinary approach required to coordinate the instances of structural safety with those of the energy performance of the building, often kept as separate needs by traditional approaches. (Reggio et al., 2019) For, if the exoskeleton of insects is not only a tool for the self-support and movement, though also the skin itself as an organ of control, sensation and exchange with the exterior environment, much the same way the employment of this methodology for the retrofit of existing constructions implies the addition of a new, layered and high performance facade, able to consistently improve the energy standards of the whole building. As a holistic renovation tool, the Adaptive Exoskeleton might contribute to the redefinition of the poor physical properties of ageing and out of date large scale residential complexes of the past century. (Feroldi et al., 2014) (Marini et al., 2017)

The vast majority of these buildings belong to a pre-regulation era, in which no particular consideration of the environmental impact of buildings and their energy efficiency was required in the design of new quarters. At the same time, the strong direction that was undertaken towards fast and standardised construction processes (as a response to the severe housing shortage and impetuous urbanisation) led often, without exceptions for the most qualitative developments, to the employment of technologies mainly by virtue of their economical and constructive advantages, regardless of the concern of their maintenance and conservation over time. It is for these reasons that the entirety of this consistent part of the modern heritage presents severe lacks in physical terms: poor thermal and acoustic insulation of opaque and transparent enclosures, issues connected to systematic condensation and recurring thermal bridges among the frequent bare building structural components. Nevertheless, the effects of weather and the inevitable deterioration of materials cause the gradual decay over time of building components. (Mortarotti et al., 2017) While a simple conservative approach would imply the repair of the original components, the legitimate ideal of passive conservation methodologies, ordinary repair and maintenance routines is often at odds with the needs for buildings that are adapted, fitted to their environmental context. The additive-external approach of the Adaptive Exoskeleton is, in other words, a design strategy in this direction of research. In first place, because the operation of adding materials to the exterior of buildings allows for a complete redesign of these buildings, as to remodel what exists to contemporary claims and expectations; yet, concurrently, the redesign of the building's envelope allows for a dramatic enhancement of the environmental properties control

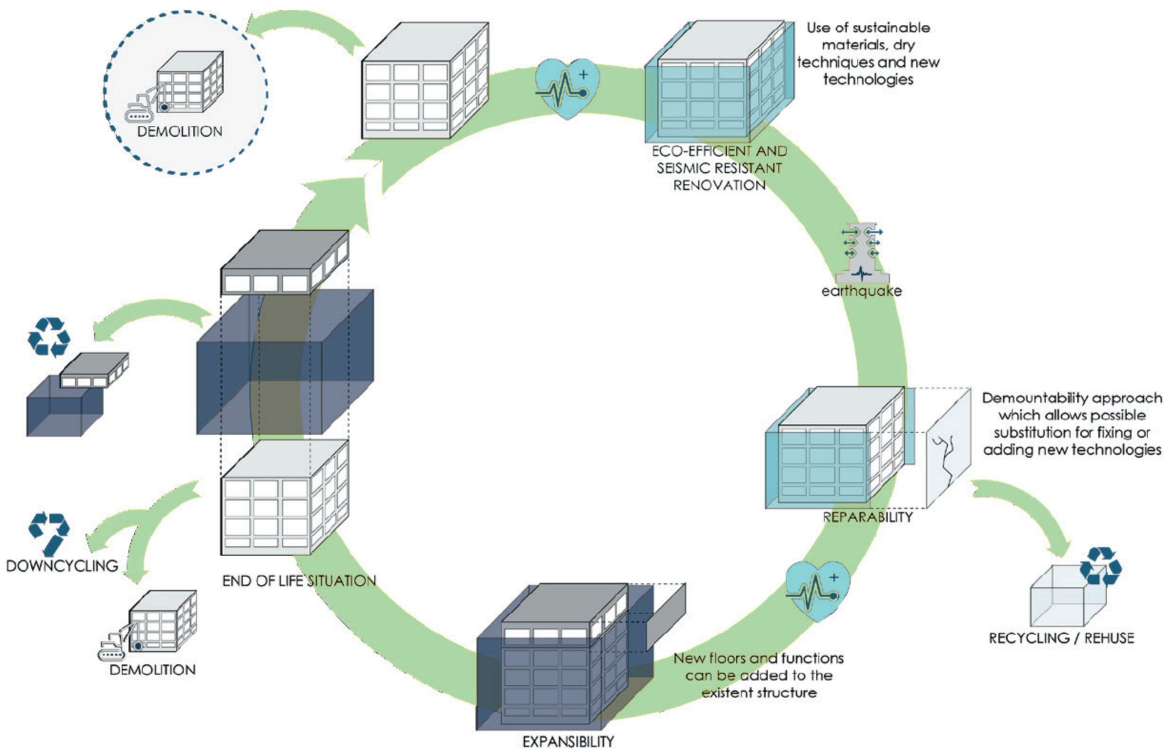


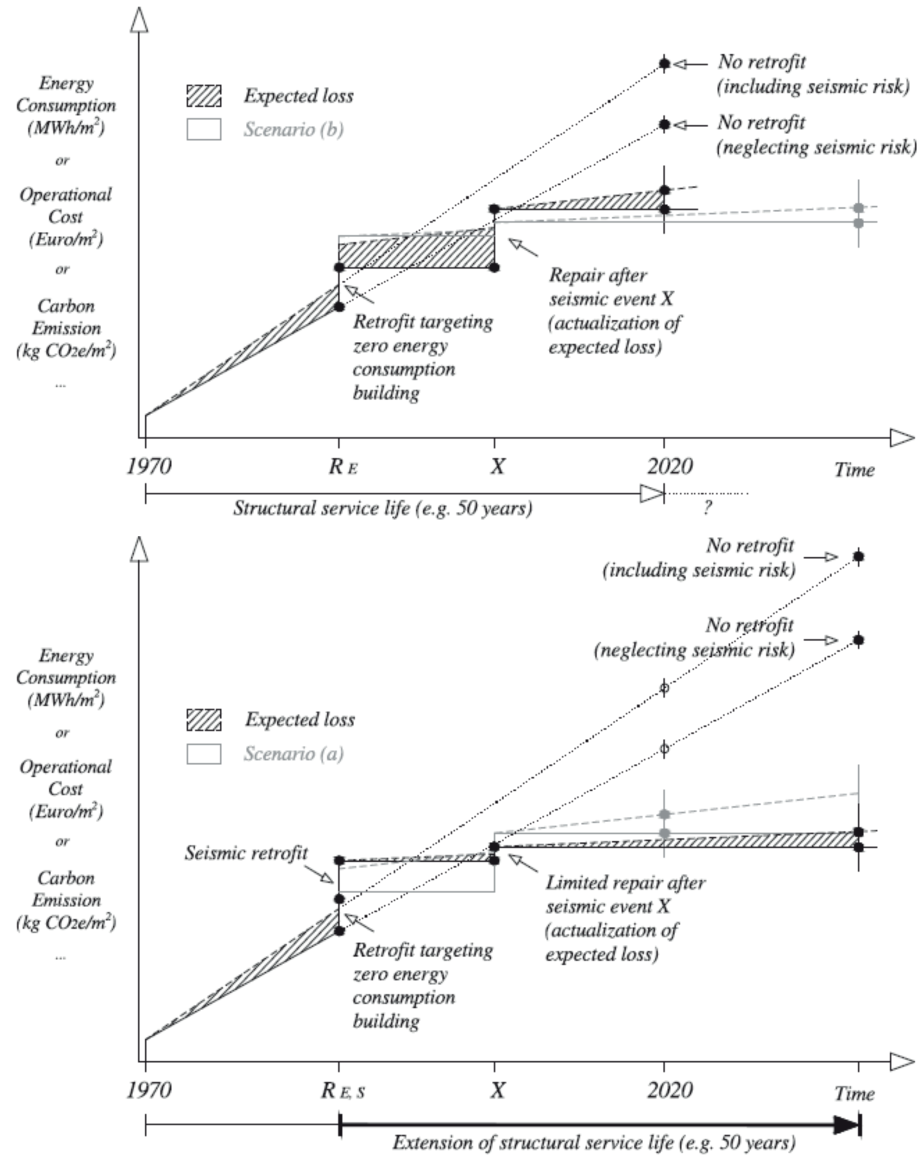
Figure 02
Life Cycle Thinking: whole life savings of the exoskeleton approach

of the existing asset. Envelopes of past buildings were hardly conceived as devices for the environmental control and reduction of energy waste, rather as solely morphological, technical or structural components. As if to add these new values, peculiar of the contemporary sensibility towards the built environment, the employment of an additive strategy appears to be the most proficient option for the integration of modern technologies on old buildings. (Gaspari, 2012) In this regard, the renewed building's skin might as well be seen as a new protective layer of what exists underneath, ultimately aiming at the conservation of function and vitals of the ageing built environment, still with the least interference with the everyday life of its inhabitants and users: a sort of moulting, to mention once again the biological metaphor with insects. As a tool for the deep energy retrofit of buildings, the Adaptive Exoskeleton might be conceived as the external supporting framework, absolving and most of the environmental tasks that the original building is unable to cope with an appropriate degree of performance, or providing additional space to host renewed functionalities to further improve the impact of the retrofit on the energy consumption. In particular, two possible categories of reconfiguration are at hand for the designer: employing passive or active systems. The first implies the ability of the exoskeleton itself to control the thermal properties of the existing envelope without the need for further operational energy, the latter the introduction of active systems, that employ energy to positively affect the overall environmental performance of the building. (Gaspari, 2012)

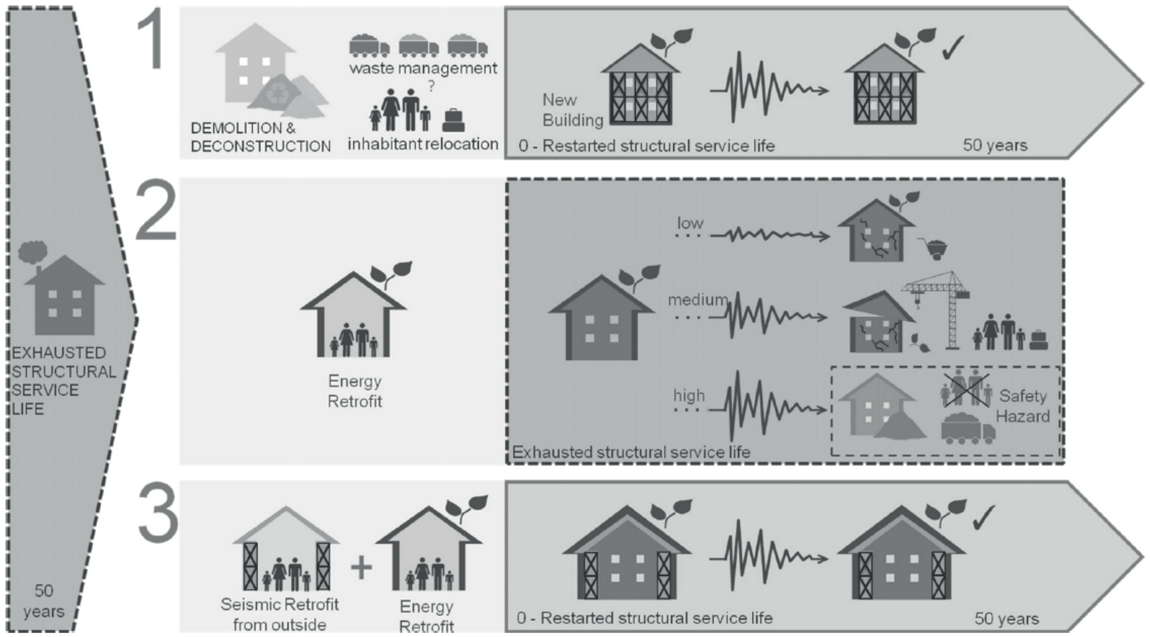
Figure 03
Impact on energy consumption, operational costs or carbon emission throughout the life-cycle (Belleri and Marini, 2015)

Above: energy retrofit intervention

Below: joint energy and seismic retrofit interventions



Hence, the deep retrofit by means of an external Adaptive Exoskeleton is far more than a simple enhancement of the energy efficiency, being in fact a effective solution towards the objective of an integrated and systemic redesign of the overall physical behaviour of the building. The ultimate goal is that of a consistent reduction of *Operational Energy* (OE): defined as the annual amount of non-renewable energy needed by the complex of living functions of the building. It refers, in other words, to the *Primary Energy Demand* (PED) for heating, cooling, hot water production, lighting and domestic appliances, measured in kWh/m^{2}yr. (Giordano et al., 2015) Other indicators, with a growing popularity, of the same operational expenses of energy are those employing the carbon equivalent concept (kg$CO_{2,eq}$/m^{2}yr) or that of potential greenhouse emissions (CO_{2e}). (Baeli, 2013)



For, if the introduction of these new technologies is the strategy to follow in order to reduce to a minimum the operational energy demand, another aspect has to be taken into careful consideration: the *Embodied Energy* (EE) of the new elements. EE is defined as the amount of non -enewable forms of primary energy required for the entire life-cycle: its components are the extraction of raw materials, the transformation of these into semi-finished or finished products, their transportation and replacement on site and their displacement at the end of the useful life. **(Giordano et al., 2015)** In order to make the transformation truly sustainable, it is fundamental that the sum of the contribution of the value of EE of each of the new additions does not overweight the achieved savings in operational energy across the time frame of the renewed life-cycle of the artefact. **(Gaspari, 2012)** Furthermore, it will be necessary to put into account the entire amount of energy and the environmental impact of the adaptation process, necessarily involving the demolition of (thought contained) parts of the existing building, with the consequential production of waste and its disposal, and the employment of construction machines and devices. **(Maninchedda, 2019)** It is right in this direction that the employment of the Adaptive Exoskeleton methodological approach deploys its maximum efficacy: the improvement of structural safety can effectively improve the environmental performance, in particular in situations in which the risk factor cannot be overlooked and a typical retrofit approach could not cope with the damages brought about by severe seismic events. **(Belleri and Marini, 2015)** Last but not least, the addition of an external open-structure might at the same time improve the flexibility and redundancy of the existing artefact, ultimately allowing for further savings in terms of adaptation energy in case of necessity of future updates by the building's users, or in case of extreme natural events.

Figure 04

Conceptual map of three different scenario (Belleri and Marini, 2015)

Above: demolition and reconstruction (substitution)

Middle: energy upgrade

Below: joint structural and energy retrofit

Figure 05

Multiple roles of the building envelope

Partial reworking from: Herzog, Knippers and Lang (2017)

ENVELOPE

OUTSIDE	Control | protection	INSIDE
Climate:		**Comfort requirements:**
Solar radiation	**Daylight transmittance**	Comfortable illuminance
Air temperature	**Thermal insulation**	Comfortable temperature
Humidity	**Thermal capacity**	Comfortable humidity
	Vapour tightness	
Air pollution	**Air tightness**	Comfortable air quality
Precipitations	**Water tightness**	Protection from weathering agents
Other actions:		
Sounds/Noise	**Acoustic insulation**	Comfortable acoustics
Mechanical loads (wind, impacts)	**Impacts protection**	
Electromagnetic radiations	**Sheltering**	**Safety requirements**
Fire	**Fire protection**	
Other contextual factors:		**General requirements**
Socio-cultural context	**Public | Private**	Privacy
	Sensitivity	Representativeness
Available resources	**Redundancy**	Economy (financial)
		Ecology (life-cycle)
		Functionality
		Durability
		Maintenance
		Disposal

Double skin envelope: a passive strategy

The envelope is, just as the skin of living beings, the ultimate boundary between inside and outside, between the private space of a dwelling and the rest of the environment. Its role is to control the exchanges between the closed system and the ecosystem and to protect the interior from the action of atmospheric conditions. Since the complex of external boundary conditions is self-evidently uncontrollable by the designer, the technological components of the envelope (the system of vertical or horizontal, opaque or transparent surfaces that border the inside spaces) are the only design objects for the separation and filter between the changing environmental conditions and the inner living habitat. Outside contextual conditions (whether they are related to climate, weathering or human actions and other contextual factors) and requirements about the qualities of the inner space are the main drivers for the design of the envelope's properties of control and protection **(Herzog, Knipper and Lang, 2017)** Hence, the envelope is the main device addressed to the passive control of inner thermal conditions. The act of sheltering is an atavistic instinct of man, and the characteristics of the shelter have been linked ever since with the contextual conditions given by the environment; however, as our understanding of the environment is in contemporary times far more complex and scientifically aware, the design of building envelopes becomes less and less an easy task. Envelopes today are highly technological, multi layered instances, whose objective is to optimise the exchanges between the inside and the outside reducing at the same time the impact of buildings. **(Reichel and Schultz, 2015)**

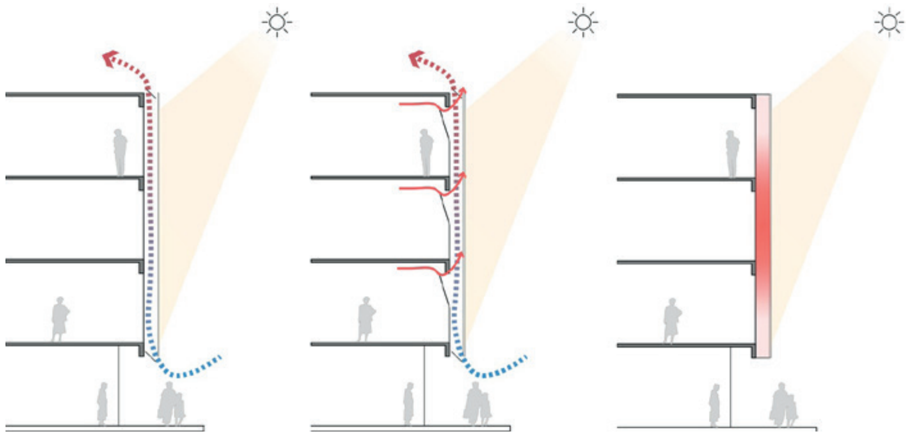


Figure 06 (Left)

The double skin envelope concept

Left: summer behaviour (as a ventilated facade)

Centre: summer behaviour with operable openings (natural ventilation)

Right: winter operation (the sunspace, or winter garden) collects heat through greenhouse effect

Engineered double skin envelopes are a passive strategy to reduce heat dispersion, while at the same time maximising heat gains by solar radiation and natural ventilation. Although the concept is not new, a recent growing trend is their application in skyscrapers' design, for their highly transparent aspect, thermal and acoustic performance, reduced air conditioning and installation costs of specific opening technologies, given the large facade on floor space ratio of this typology. **(ArchDaily, 2020)** Furthermore, their application has developed into a considerable amount of different technological solutions. What matters the most is the design of natural air intake and expulsion: closed cavity systems (which forbid any exchange of air between the inside, the cavity and the atmosphere) or ventilated systems are the main two typologies, which can be further divided according to the several different layouts (horizontal or vertical) for the ventilation of spaces. **(Baunetz Wissen, 2020)** Furthermore, regarding the degree of transparency of the envelope, the heat gain provided by double skin facades can be direct (wide, glazed openings) or indirect (Trombe wall principle, combined effect of an highly transparent external screen in front of prevalently opaque and heat capacitive interior partitions). **(Gaspari, 2012)**

Within the context of a deep energy redesign of existing buildings, this passive strategy is often pursued by adding external layers of lightweight, dry construction steel-glass frames. These can provide additional floor space to the former building, creating buffer zones (also known as winter gardens or sunspaces), whose flexible and ambiguous function is able to provide, along with the improved passive efficiency of the envelope, an important reserve for redundancy and adaptability of the interior living spaces. **(Druot, Lacaton and Vassal, 2007)** The application of this strategy on the existing stock, however, must be carefully analysed according to the construction and maintenance costs. **(Gaspari, 2012)** Furthermore, while the application the double skin technology is widely appreciated in cold and temperate climates, its functional and environmental performance requires a particular attention, in warmer climates such that of the Mediterranean area, to the avoidance of overheating phenomena (to be avoided employing adequate shading and ventilation) **(Fotopoulou et al., 2018)**

Figure 07 (Next page, images)

Lacaton & Vassal, *Transformation de 530 logements*, Bordeaux (France), 2016

Elevations and close up, before and after the transformation.

The additive strategy employed by the architects allowed for a fast, economic and less invasive renovation process, still achieving a deep renewal of all the 530 apartments. The new envelope's winter gardens improve the dwellings' efficiency and living conditions.

Building U-Values before/after retrofit: (Slessor, 2019)

Roof:
Before 0.74
After 0.18

Exterior walls:
Before 2.12
After 0.24

Floors (over basement):
Before 2.27
After 0.34

Windows:
Before 4.20
After 1.70

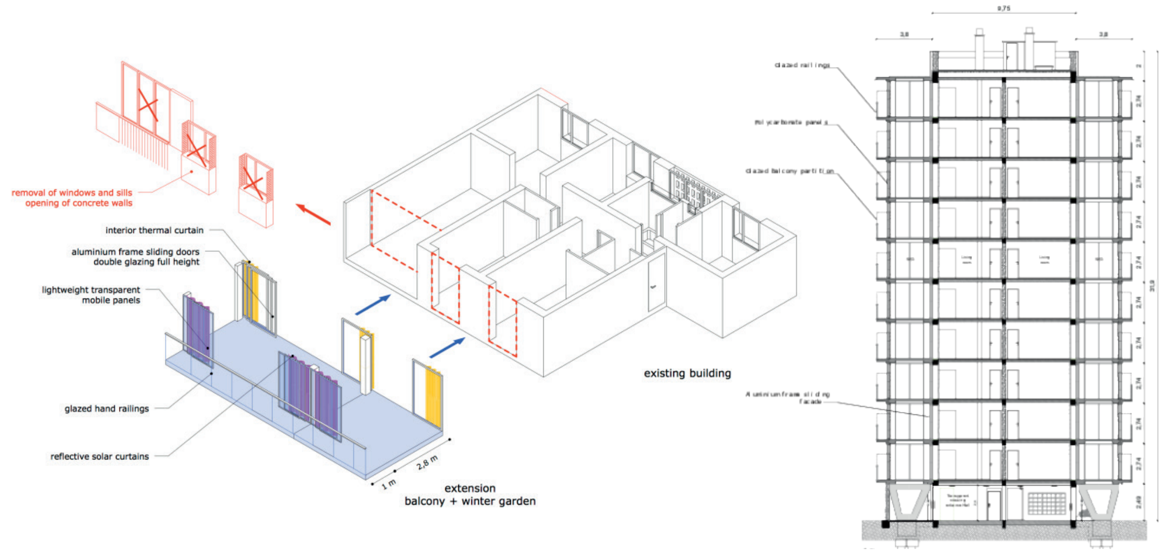


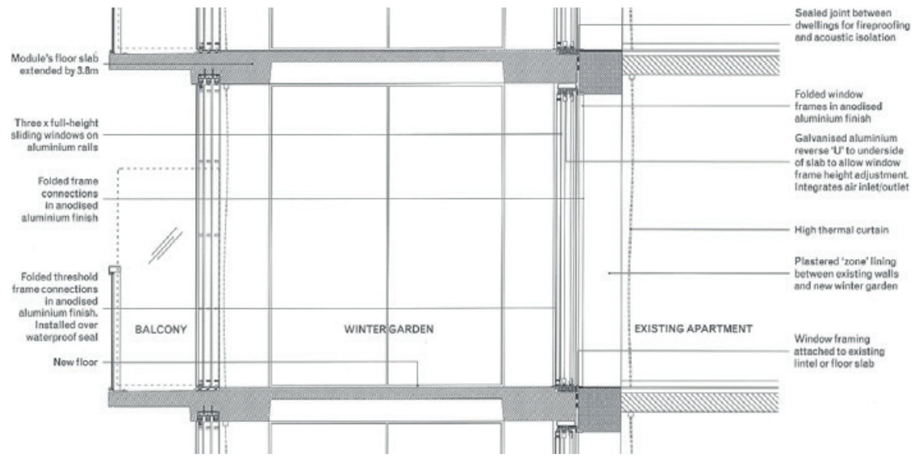
Figure 08 (Drawings)

Lacaton & Vassal, *Transformation de 530 logements*, Bordeaux (France), 2016

Above, left: envelope retrofit methodology

Above, right: cross section

Below, right: detail section through winter garden and balcony (Slessor, 2019)



General energy requirements for buildings

The up to date minimum requirements and performance targets for new constructions and retrofits have been recently implemented in the Italian codes in 2015,[03] abrogating the previous law (dating back to 2009).[04] In particular, the directive 2010/31/EU on the energy performance of buildings and the 2009/28/EC on the use of energy from renewable sources have been merged. Main objective is to promote the enhancement of energy efficiency in buildings, with regard to the specific local climate conditions, comfort requirement for interior spaces and cost effectiveness of the technologies employed. Entered into force on October 1st of the same year, the D.M. describes the application calculation methodologies, building's certification and mandatory minimum requirements. **(Corrado, 2016)**

The calculation of the energy efficiency of buildings aims at defining the primary demand for non-renewable operational energy, and is based on the holistic methodology promoted by the European Commette of Standardisation to support the European directives, known as EPBD.[05] The Italian institutes for standardisation (UNI and CTI) have adopted this methodology with the CTI R14 (2013) procedure and, subsequently, within the UNI/TS 11300 thread,[06] regarding the assessment of building energy performance. The annual amount of the energy demand is assessed on a monthly basis (same for the amount of renewable energy) and is indeed the sum of the contribution of each energy-consuming service. Hence, the final primary energy demand value is the difference between the total energy demand and the amount of energy from renewable sources. The total energy demand is however considered in the design verifications against the minimum requirements: for the conversion of both contributions, the standard provides the conversion factors for each energy vector. The conversion factor in total primary energy is:

[1] $f_{P,tot} = f_{P,n\text{-}ren} + f_{P,ren}$

Where:

$f_{P,n\text{-}ren}$*: conversion factor in non-renewable primary energy*

$f_{P,n\text{-}ren}$*: conversion factor in renewable primary energy*

The D.M. goes on defining the typologies of interventions: new construction (including substitution and extension or addition of storeys), major renovation (first and second level) and energy refurbishment. While the definition of these, with particular attention to those regarding the actions on existing buildings, is not strictly bounded to the achievement of a certified degree of performance, rather to the description of the interventions, different levels of minimum requirements are specified. In respect to the building envelope (H'_T and $A_{sol,est}$), HVAC and hot water production systems' global seasonal efficiency (η), and the exploitation of renewable resources (% of the total energy demand). Finally, the seasonal energy demand for heating and cooling ($EP_{H,nd}$, $EP_{C,nd}$) and the global energy performance index ($EP_{gl,tot}$).

[03] D.M. 26 giugno 2015, in materia di "*Adeguamento del decreto del Ministro dello sviluppo economico, 26 giugno 2009 - Linee guida nazionali per la certificazione energetica degli edifici.*"

[04] D.M. 26 giugno 2009, in materia di "*Linee guida nazionali per la certificazione energetica degli edifici.*"

[05] E.C. n. 480/2010, "*Methodology calculating the integrated energy performance of buildings and promoting the energy efficiency of buildings.*"7

[06] UNI/TS 11300-5: 2016, in materia di "*Prestazioni energetiche degli edifici. Parte 5: Calcolo dell'energia primaria e dalla quota di energia da fonti rinnovabili.*"

and:

UNI/TS 11300-6: 2016, in materia di "*Prestazioni energetiche degli edifici. Parte 6: Determinazione del fabbisogno di energia per ascensori e scale mobili.*"

Figure 09 (Table, above)

Classification of interventions, according to the D.M. 26 giugno 2015

Figure 10 (Table, below)

Classification of energy efficiency classes of the APE, according to the D.M. 26 giugno 2015

Classification	Description
New construction (NC)	New construction (after 1st October, 2015) Substitution (demolition and reconstruction) Extension: bigger than 15% of the former building/than 500 m^3
Major renovation (1st level) (MR1)	Total renovation of the HVAC systems (winter/summer conditioning) Renovation of (minimum) 50% of the former envelope
Major renovation (2nd level) (MR2)	Partial renovation of the HVAC systems (heating/cooling) Renovation of 25 to 50% of the former envelope
Energy refurbishment (ER)	Partial renovation of the HVAC systems (winter/summer conditioning) Renovation of less than 25% of the former envelope
Excluded interventions	Restoration/maintenance of the building envelope Maintenance of the HVAC systems

Efficiency class:	A4	A3	A2	A1	B	C	D	E	F	G
$EP_{gl,n\text{-}ren,rif,standard}$	<=0.4	(0.4, 0.6]	(0.6, 0.8]	(0.8, 1.0]	(1.0, 1.2]	(1.2, 1.5]	(1.5, 2.0]	(2.0, 2.6]	(2.6, 3.5]	>=3.5

The energy performance index is the building's total primary energy demand in one year, sum of each contribution divided by the net floor area:

[2] $EP_{gl,tot} = EP_H + EP_W + EP_V + EP_C + EP_L + EP_T \quad [kWh/m^2yr]$

Where:

EP_H*: performance index of heating systems*

EP_W*: performance index for hot water production*

EP_V*: performance index for mechanical ventilation*

EP_C*: performance index for cooling systems*

EP_L*: performance index for artificial lighting*

EP_T*: performance index for interior transportation systems*

The values thus determined are confronted with those of a so-called *reference building*. This methodology is intended to normalise the performance level of buildings against that, which would result from the strict compliance of the minimum requirements (defined according to economic, climate and socio-cultural conditions on the national territory). The *reference building* is a conceptual building characterised by the same geometrical and climate conditions of the real one, same function and occupancy conditions, same typologies of conditioning or energy production systems, while its thermal properties are those of a state of the art new building, designed observing all the minimum requirements. Its introduction is meant to avoid the influence of some external solicitations on the building's closed system and to promote optimised technical-economic solutions (by avoiding imbalance between technological solutions). **(Corrado, 2016)**

Finally, the D.M. introduced the updated energy certification documents known as APE (*Attestato di Prestazione Energetica*).[07] Ten classes of energy performance are set (from A4 to G, best to worst), defined according to the ratio ($EP_{gl,n\text{-}ren,rif,standard}$) between the total energy performance index ($EP_{gl,tot}$) of the buildings being certified and those of a simplified *reference building*.

[07] Formerly known as ACE (*Attestato di Certificazione Energetica*) in:

D.L. 4 giugno 2013, in materia di "*Disposizioni urgenti per il recepimento della Direttiva 2010/31/UE del Parlamento europeo e del Consiglio del 19 maggio 2010, sulla prestazione energetica nell'edilizia per la definizione delle procedure d'infrazione avviate dalla Commissione europea, nonchè altre disposizioni in materia di coesione sociale.*"

Parameter:	Components:	A + B		C		D		E		F	
Type of intervention:		NC/ MR	ER	NC/ MR	ER	NC/ MR	ER	NC/ MR	ER	NC/ MR	ER
U [W/m²]	Vertical opaque	0.43	0.40	0.34	0.36	0.29	0.32	0.26	0.28	0.24	0.26
	Roof	0.35	0.32	0.33	0.32	0.26	0.26	0.22	0.24	0.20	0.22
	Horizontal opaque	0.44	0.42	0.38	0.38	0.29	0.32	0.26	0.29	0.24	0.28
	Transparent	3.00	3.00	2.20	2.00	1.80	1.80	1.40	1.40	1.10	1.00
	Partitions	0.80									
g_{gl+sh} [-]	Transparent	0.35									

Figure 11

Parameters of the *reference building* (D.M. 26 giugno 2015)

In force since January 1st, 2019 for public buildings and since January 1st, 2021 for all buildings

Major renovation of the building envelope

The building envelope is the whole of surfaces that delimit the conditioned volume of a building. These can be divided into a few several functional categories: vertical opaque structures (towards exterior spaces, ground or unconditioned spaces) opaque roof structures (horizontal or sloped, towards exterior spaces, ground or unconditioned spaces), transparent or technical components (windows, comprehensive of frames, towards exterior spaces or unconditioned spaces), vertical or horizontal opaque structures dividing between units. The sum of these surfaces is the total of the building's volume dispersion surfaces.

The D.M. provides two new parameters to evaluate the global performance of the building envelope: the global average heat transfer coefficient (H'_T) (through transmission, per unit of dispersing surface) and the summer equivalent solar area (related to the surface unit) ($A_{sol,est}$ / $A_{sup,ut}$). The first parameter estimates the winter seasonal performance of the building envelope of both new constructions and major renovations.

[5] $H'_T = H'_{tr,adj} / \Sigma_K A_K$ [-]

Where:
$H'_{tr,adj} = H_D + H_g + H_U + H_A$
H_D *: average heat transfer coefficient for components towards exteriors [W/K]*
H_g *: average heat transfer coefficient for components towards ground [W/K]*
H_U *: average heat transfer coefficient for components towards non-conditioned spaces [W/K]*
H_A *: average heat transfer coefficient for components of other kind [W/K]*
A_K *: area of the k building envelope's component [m²]*

The contribution of each category (hereby divided by their technological function in the building envelope) is:

[6] $H_X = b_{tr,x} / (\Sigma A_j U_j + \Sigma l_k \Psi_k + \Sigma X_k)$ [W/K]

Where:
A_j *: area of the component j [m²]*
U_j *: thermal transmittance of the component j [W/m²K]*
l_k *: length of the thermal bridge k [m]*
Ψ_k *: linear transmittance of thermal bridge k [W/mK]*
X_k *: punctual thermal transmittance k [W/K]*
$b_{tr,x}$ *: correction factor [-]*

The thermal transmittance (U) measured in W/m²K is defined as the heat flow transmitted through the wall, by a unitary difference in temperature between the outer environment and the interior space, and by a unit of wall area, in steady state (non-dynamic) conditions. The total heat transmission is the sum of three components: conduction, convection and irradiation. For an opaque, multi layered component its value is:

[3] $U_{tot} = 1 / (R_{Si} + \Sigma R_J + \Sigma R_K + R_{Se})$ [W/m²K]

Where:
$R_{Si} = 1/h_i$ *: thermal resistance of the internal surface [m²K/W]*
$R_J = s_J / \lambda_J$ *: thermal resistance of the J layer [m²K/W]*
R_K *: thermal resistance of the K layer (inhomogeneous, air cavities) [m²K/W]*
$R_{Se} = 1/h_i$ *: thermal resistance of the external surface [m²K/W]*

The transmittance of transparent components (such as doors or windows) is the weighted average between the glazed area and all the other types of element (i.e. frame, shutters):

[4] $U_W = (A_g U_g + A_f U_f + l_{gf} \Psi_{gf}) / (A_g + A_f)$ [W/m²K]

Where:
A_g *: area of the glazed component [m²]*
U_g *: thermal transmittance of the glazed component [W/m²K]*
A_f *: area of the frame component [m²]*
U_f *: thermal transmittance of the frame component [W/m²K]*
l_{gf} *: length of thermal bridge between glass and frame [m]*
Ψ_{gf} *: linear transmittance of thermal bridge between glass and frame [W/mK]*

The D.M. provides the values of a reference building's for two parameters of the building envelope: thermal transmittance and solar transmission factor, the latter addressing the transparent surfaces, the first both the opaque and transparent components. The solar factor of glazed components (g_{gl+sh}) is the percentage of incident thermal energy from natural daylight on the surface of the component is transmitted to the interior.

The different values of the maximum H'_T are associated with the type of intervention and with the climate zone of the building. Other than that, these values are also specified in relation to three characteristic intervals of the *compactness factor* S/V (the total amount of envelope's surfaces divided by the total volume enclosed by the envelope itself). However, the global average heat transfer coefficient is often verified when, in the design of major renovations, the planner approaches the components' values of the target building for each climate zone and type of intervention, even without going beyond them. It is, on the other hand, thought to influence heavily the assessment of the winter performance of buildings with a relevant portion of transparent areas, where the simple compliance of the glazed elements to low values of thermal transmittance is not sufficient to guarantee the overall comliance of the envelope to the requirements in terms of global average heat transfer coefficient. (Corrado, 2016)

On the other hand, $A_{sol,est} / A_{sup,ut}$ quantifies the ability of the building to receive thermal inputs of sunlight. The site characteristic value of solar radiation on an horizontal plane in the warmest month of the year (conventionally July) is normalised with regard to that of the reference location of Rome:

[7] $$A_{sol,est} = \Sigma F_{sh,ob} \times g_{gl,sh} \times (1-F_F) \times A_{W,p} \times F_{sol,est} \qquad [m^2]$$

Where:

$F_{sh,ob}$: reduction factor for shading relative to external elements (for the effective solar collection area of the glazed surface k, month of july) [-]
$g_{gl,sh}$: total solar energy transmittance of the component (month of july, full employment of the shading components [-]
F_F : fraction of the area of the frame (in relation to the total area $A_{W,p}$) [-]
$A_{W,p}$: total projected area of the glazed component [m^2]
$F_{sol,est}$: normalised correction of factor of the incident radiation [-]

Once this value is divided by the total surface of building's storey being analysed, the non-dimensional factor summer equivalent solar area must comply to the maximum values admitted. For buildings with wide glazed openings, the evaluation of this parameter forces the designer to take into consideration shading strategies: the reduction of solar transmittance of the glass used for windows and transparent walls, as well as hardware shading devices. The use of interior shading systems is nearly always required, given the minimum $A_W / A_{sup,ut}$ ratio of at least 1/8, while the use of external shading objects become a necessity for ratios higher than 15%. **(Corrado, 2016)**

Other than the specific requirements for H'_T and $A_{sol,est} / A_{sup,ut}$ values, the D.M. prescribes the verifications to be conducted for each component. In particular, with regard to the issue of moisture, it must be verified that the eventuality of superficial and interstitial condensations is avoided.[08] With reference to the problem of superficial moisture, the calculation of the inner superficial temperature factor defines the specific component's minimum requirement in terms of thermal resistance (R). To avoid interstitial condensation it must be verified that, along the entire depth of a multi layered horizontal of vertical element towards the exterior environment (in particular when temperatures are low and humidity is high), the vapour pressure of saturation (function of the temperature at each layer's end) is higher than the vapour pressure in each point. The input climatic data of temperatures and average relative humidity of the atmosphere are defined by the technical norms.[09] Those regarding the internal conditions are assumed (starting from the external vapour pressure data) with the use a pressure difference, depending in turn on the function and vapour intensity of the building's uses (i.e. residential, commercial).[10] The evaluation of components within the dynamic domain is not mandatory, unless the building is not situated in an area characterised by mean values of irradiance on the horizontal plane higher than 290 W/m² in the warmest summer month (usually july). If this would be the case, the values of periodic thermal transmittance (Ψ) and mass surface (M) must be confronted with the minimum ones. The first parameter assesses the

[08] UNI EN ISO 13788:2013, in materia di "*Prestazione igrotermica dei componenti e degli elementi per edilizia - Temperatura superficiale interna per evitare l'umidita' superficiale critica e la condensazione interstiziale - Metodi di calcolo.*"

[09] *Ibid.*

[10] UNI 10349-1:2016, in materia di "*Riscaldamento e raffrescamento degli edifici - Dati climatici - Parte 1: Medie mensili per la valutazione della prestazione termo-energetica dell'edificio e metodi per ripartire l'irradianza solare nella frazione diretta e diffusa e per calcolare l'irradianza solare su di una superficie inclinata.*"

Figure 12

Requirements for the building envelope (D.M. 26 giugno 2015)

In force since January 1st, 2019 for public buildings and since January 1st, 2021 for all buildings

H'_T [W/m²K]	A + B		C		D		E		F	
Type of intervention: / Building's typology:	NC	ER	NC	ER	NC	ER	NC	ER	NC	ER
S/V > 0.7	0.58		0.55		0.53		0.50		0.48	
0.7 > S/V > 0.4	0.63	0.73	0.60	0.70	0.58	0.68	0.55	0.65	0.53	0.62
S/V < 0.4	0.80		0.80		0.80		0.75		0.70	

$A_{sol,est}/A_{S,util}$ [-]	Residential	Other functions
Type of intervention:	0.03	0.04

ability of an opaque partition to phase out and attenuate the periodicity of the thermal flow, the second measures the mass in Kg per surface unit.[11] Additionally, the designer must evaluate locally the efficacy of the employed shading devices, whether fixed or operable, and, in order to reduce energy consumption for cooling and the urban heat island effect, the eventuality of passive strategies of natural ventilation. Contextually, the solar reflectance of roof's materials must be checked against he minimum requirements.

Both thermal insulation and the amount of solar thermal energy, qualities of the building envelope, have a crucial role in defining the overall demand for energy, in particular that needed for heating and cooling, which dramatically affects the environmental performance of constructions.[12] The need of energy for heating in the winter season is defined as:

[8] $$Q_{H,nd} = (Q_{H,tr} + Q_{H,ve}) - \eta_{H,gn} \cdot (Q_{int} + Q_{sol,w}) \qquad [MJ]$$

Where:

$Q_{H,tr}$: exchange of energy by transmission [MJ]
$Q_{H,ve}$: exchange of energy by ventilation [MJ]
$\eta_{H,gn}$: coefficient for the utilisation of sources of thermal energy [-]
Q_{int} : thermal energy input (due to internal sources) [MJ]
Q_{int} : thermal energy input (sun radiation through glazed areas) [MJ]

While, in warmer summer months, the amount of energy needed to cool the inner spaces is estimated as:

[9] $$Q_{C,nd} = (Q_{int} + Q_{sol,w}) - \eta_{C,ls} \cdot (Q_{C,tr} + Q_{C,ve}) \qquad [MJ]$$

Where:

$Q_{C,tr}$: exchange of energy by transmission [MJ]
$Q_{C,ve}$: exchange of energy by ventilation [MJ]
$\eta_{C,ls}$: coefficient for the utilisation of thermal energy dispersion [-]
Q_{int} : thermal energy input (due to internal sources) [MJ]
Q_{int} : thermal energy input (sun radiation through glazed areas) [MJ]

Finally, the energy demand for heating and cooling ($EP_{H,nd}$, $EP_{C,nd}$), expressed in kWh/m²y, references the $Q_{H,nd}$ and $Q_{C,nd}$ to the conditioned net floor area (prior conversion of MJ in kWh). Their amount is determined by the users' behaviour (related by the norms to the function): each volume of a building (or entire building) characterised by continuity of these properties is called a *thermal zone*, whose need for energy must be evaluated individually.

[11] UNI EN ISO 13786:2018, in materia di "*Prestazione termica dei componenti per edilizia - Caratteristiche termiche dinamiche - Metodi di calcolo.*"

[12] UNI/TS 11300-1, in materia di "*Prestazioni energetiche degli edifici - Parte 1: Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva ed invernale.*"

The issue of knowledge

As an approach for the regeneration of the existing stock, the design of deep energy retrofits begins with the knowledge of the built artefacts. In particular, it is fundamental that the designer gathers the correct geometrical properties, as well as those of materials and technical equipment, in order to assess the weaknesses and possibilities of intervention on the existing stock. The problem is all in all similar to that presented by the issue of the structural knowledge of the building: with regard to the modern heritage, it is possible to access to a much broader official documentation regarding the construction of existing buildings. These information alone, however, are not sufficient to guarantee a correct understanding of the exact present state of performance: the presence of uncertainties about the observance of this documentation in the construction stage, the inevitable decay of materials, that caused by weathering and the frequent, spontaneous modifications that the users introduce to their dwelling units might have altered consistently the initial configuration of the case study. The presence of up to date technologies of non-destructive measurement implies, as well, a great improvement in the ability to assess the exact physical behaviour of a building, being able to gather information that are invisible to the naked eye (thermal transmission of the components). However, also this new possibility for improved detail and reliability of on-site measurements must be carefully managed by the ability of the designer. Furthermore, being impossible for the designer to access to such instrumental data, the technical regulations offer a plethora of standardised databases of materials' properties, in particular with regard to the peculiar characteristics of constructions on the national territory.[19]

The same idea of a possible data standardisation about some specific building's typologies lies at the core of the recent *TABULA* (Typical Approach for Building Stock Energy Assessment) research project. Main objective of this research is to address the necessity of data about the existing heritage in order to perform expeditious audit operations, finalized at empowering policy makers and designers with consistent tools for the evaluation and comparison of the impact of possible retrofit scenarios. This project, in particular, has been directed prevalently to the housing sector. To begin, the residential stock is divided into categories by its age. To each, a set of four distinct building's typologies is assigned: single family hoses (SFH), terraced houses (TH), multi-family houses (MFH) and apartment blocks. Each is characterised, in each time frame, by different parameters and technologies of the building envelope, as well as by different technical equipments and conditioning performance, based on a collection of statistical data about the heritage of the European nations that took part to this project. The retrofit scenario are defined, instead, as typical or advanced. The final output is the definition of *target buildings* for different performance levels, in order to assess the effectiveness of future retrofit proposals. (Corrado et al., 2014)

[19] UNI 10351:2015, in materia di "Materiali e prodotti per edilizia. Proprietà termoigrometriche. Procedura per la scelta dei valori di progetto"

and:

UNI 10355:1994, in materia di "Murature e solai. Valori della resistenza termica e metodo di calcolo."

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RETROFIT PROPOSAL

The *Corso Sebastopoli* neighbourhood

A piece of land (72 hectares, 74 ares and 94 centiares in the territory of Turin and 92 ares and 64 centiares in the territory of Grugliasco), centuries long a farmland owned by the inhabitants of the *Giajone* farmhouse, changes ownership, with an official deed dated 8 March 1920, and is divided in 1926 into four different properties. The fourth, 13 hectares, 91 ares and 77 centiares belongs now to Mr. Antonio Galli. It is with the Galli family that the engineer Alberto Benni (of the *INA-Casa* management) negotiates for the sale of 114.389m² of this parcel, a transaction worth 414.259.763,50L (3.621.50L/m²) and completed on September 11th, 1956. **(Libert, 2017)**

The area is destined to an affordable development for workers, within the context of the national *Piano Fanfani*[01] for the development of public housing in industrial areas. The IACP (*Istituto Autonomo Case Popolari*) acted as the public contracting authority, launching in october 1957 the tender for the four lots among which the whole area has been diveded: 10950, 10951, 10952, 10953. An additional lot had been contracted by INCIS (*Istituto Nazionale per le Case degli Impiegati dello Stato*) for the construction of two further towers, that will eventually be taken over by the same IACP in 1962. The total amount of construction works is divided into four lots, respectively assigned to the contractors: Milanesio Costruzioni, S.A.I.C.C.A. (second and fourth lots), Bottoli Giulio. Some other relevant construction companies of the time took part to this public tender: among the others, Nervi e Bartoli (led by Pier Luigi Nervi) and Dolza (led by the homonym family of engineers, constructors and architects that will contribute consistently to the public and private housing development of Turin in the 60s and 70s).

Construction works on the five different building sites (divided between the four lots) began between the end of 1957 and the beginning of 1958. The lot 10951 (auction base 423.000.000L, winning bid 422.577.000L) was the first to take off on December 31st 1957. It included 6 buildings, a total of 220 apartments and 1180 rooms, at an expected average construction cost of less than 450.000L for each room. The general economic framework included an amount of total investment by the *INA-Casa* management of 2.010.660.000L (unit price of 465.000L for each of the total 4324 rooms). The new 816 IACP affordable apartments (excluding those contracted by INCS) were divided among three typologies: 5, 6 or 7 rooms. The provision of services and connection to urban infrastructures (i.e. sewage, electricity, internal roads and sidewalks, ground levelling works, external paving) accounted for a total expense of 53.602.489L. **(Libert, 2017)**

[01] L. 28 febbraio 1949, n.43, in materia di "*Provvedimenti per incrementare l'occupazione operaia, agevolando la costruzione di case per i lavoratori.*"

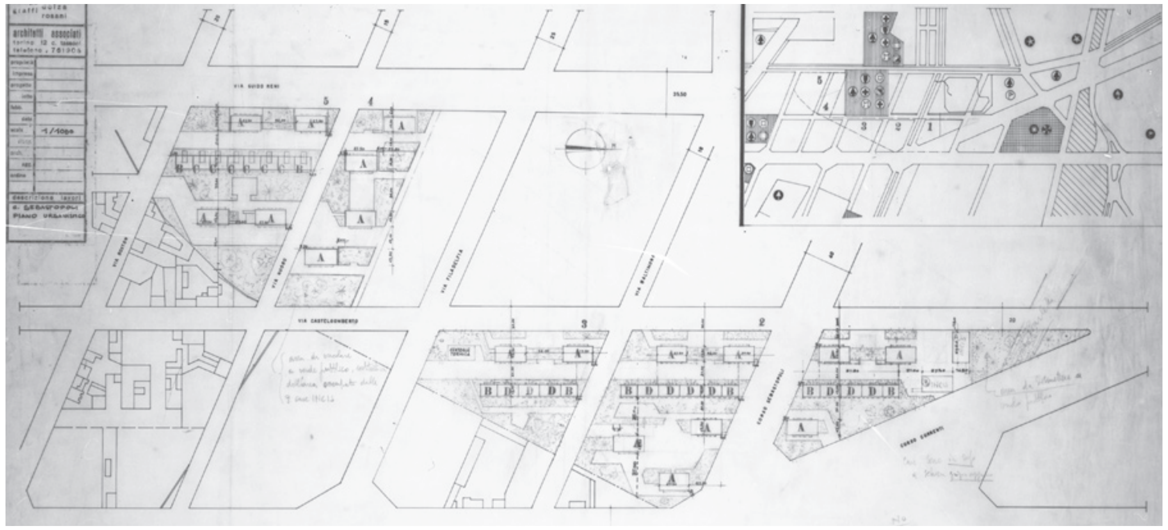


Figure 01
General plan, layout of the INA-Casa development (1958)
Original drawing, with the indication of the 5 different areas and of building's mark.

The construction works proceeded with a moderate amount of delay; however, the regular site inspections assessed the proper quality degree of the process. A site inspection dated August 1st 1959 reports that the buildings of the 10951 lot are finished, besides some finishes in particular regarding the commercial ground floors. The building site results however dismantled, the provision and connection to services is proceeding. Additional delays occurred, however, during the static testing stage, due to the bankruptcy of one of the contractors (S.A.I.C.C.A). The financial issues protracted for a couple of years: new inspections occurred in 1960 and 1961; the static test reports were finally signed by the bankruptcy trustee on December 12th 1962, final act of the whole process. **(Libert, 2017)**

The first inhabitants arrived already in the late 1959, and by the first half of the 60s the neighbourhood was definitely settled. The allocation of the apartments was entrusted to the different enterprises and companies, employers of the workers' family that obtained an apartment. Both public employers (i.e. INPS, RAI, Banca d'Italia, Guardia di Finanza) and private enterprises (Cogne, Olivetti, Nebiolo, Lancia) were among the assignees. These subjects were contracting directly with IACP, reserving some of the dwellings for their employees, a different procedure from that common to many other developments, especially those led by the bigger companies at that time (FIAT above all), which could afford the construction and management of a large number of apartments at their expenses. The new residents were, demographically speaking, coming from anywhere in Italy, in particular from the southern regions, Calabria, Sicily and Puglia among the others, but also from Veneto and from Piedmont itself; among the fewer foreigners, Istrian and Greeks. To the new inhabitants, the *INA-Casa* management proposed contracts with a future sale agreement: the typical rent for a 5 rooms apartment amounted to 16.785L, comprehensive of the lease of the apartment and of a contribution to the national body of management of the *INA-Casa*, taken over in 1963 by GESCAL.[02] **(Libert, 2017)**

[02] L. 14 febbraio 1963, n.60, in materia di "*Liquidazione del patrimonio edilizio della Gestione I.N.A Casa e istituzione di un programma decennale di costruzione di alloggi per lavoratori.*"

BUILDING LOTS:	Contracting Authority	Buildings #	Auction base [£]	Winning bid [£]	Discount	Contractor
10950	IACP	1	283.600.000,00	273.674.000,00	-3,50%	Milanesio Costruzioni
	IACP	1				
	IACP	1				
	IACP	1				
16507	INCIS	2	-	-	-	
10951	IACP	1	423.000.000,00	422.577.000,00	-0,10%	S.A.I.C.C.A.
	IACP	1				
	IACP	1				
	IACP	1				
	IACP	1				
	IACP	1				
10952	IACP	1	224.200.000,00	216.240.900,00	-3,55%	Bottoli Giulio
	IACP	1				
	IACP	1				
10953	IACP	1	622.500.000,00	621.877.500,00	-0,10%	S.A.I.C.C.A.
	IACP	1				
	IACP	1				
	IACP	1				
	IACP	1				
	IACP	1				
	IACP	1				
	IACP	1				
	IACP	1				
TOTALS:	-	24	1.553.300.000,00	1.534.369.400,00	-1.20%	-

Planning and design phase

The planning and design phase of the urban complex of residential buildings happened between 1957 and 1958. The winning design was that of a team led by the architects Carlo Mollino (1905-1973), Carlo Alberto Bordogna (1913-1998) and Nino Rosani (1909-2000), the architect and entrepreneur Francesco Dolza, the architects and furniture designers Franco Campo and Carlo Graffi. In its initial stage, four different design options were proposed. **(Pace, 2010)** However, not everything went as the design team could have imagined: it is remarkable the correspondence between Carlo Mollino and Carlo Villa, president of Turin's IACP. In a letter in 1957 he wrote:

Figure 02 (Above)

Subdivision of lots and tender details, definition of the contractors

The tender phase happened all through1957 and 1958, along with the conception and design stage of the complex.

URBAN BLOCKS:	Construction began:	Address	Mark	Apartments (room #)			Totals		Service began:
				5	6	7	Apartments	Rooms	
1	Beginnig 1958	Corso Sebastopoli 298	Tower A	24	8	0	32	168	01.10.1959
		Via Castelgomberto 21	Tower B	24	8	0	32	168	
		Corso Sebastopoli 286	Tower C	24	8	0	32	168	
		Corso Sebastopoli 294	Block	30	10	10	50	280	
		Via Castelgomberto 11 Via Correnti 58	Towers INCIS	-	-	-	-	-	
2	31.12.1957	Via Castelgomberto 35	Tower A	24	8	0	32	168	01.10.1959
		Corso Sebastopoli 287	Tower B	24	8	0	32	168	
		Via Baltimora 152	Tower C	24	8	0	32	168	
		Corso Sebastopoli 273	Tower D	24	8	0	32	168	
		Corso Sebastopoli 267	Tower E	24	8	0	32	168	
		Corso Sebastopoli 283 Via Baltimora 160	Block	34	12	24	60	340	
3	Beginnig 1958	Via Castelgomberto 51	Tower A	24	8	0	32	168	01.10.1959
		Via Baltimora 161	Tower B	24	8	0	32	168	
		Via Baltimora 157	Row	34	12	24	50	280	
4	Beginnig 1958	Via Guido Reni 125	Tower A	24	8	0	32	168	01.10.1960
		Via Nuoro 42	Tower B	24	8	0	32	168	
		Via Nuoro 40	Tower C	24	8	0	32	168	
		Via Nuoro 38	Tower D	24	8	0	32	168	
5	Beginnig 1958	Via Guido Reni 139	Tower A	24	8	0	32	168	01.10.1960
		Via Guido Reni 133	Tower B	24	8	0	32	168	
		Via Nuoro 35	Tower C	24	8	0	32	168	
		Via Nuoro 37	Tower D	24	8	0	32	168	
		Via Nuoro 39	Block	-	-	-	80	500	
TOTALS:	-	-	-	606	176	34	816	4324	-

Figure 03 (Above)

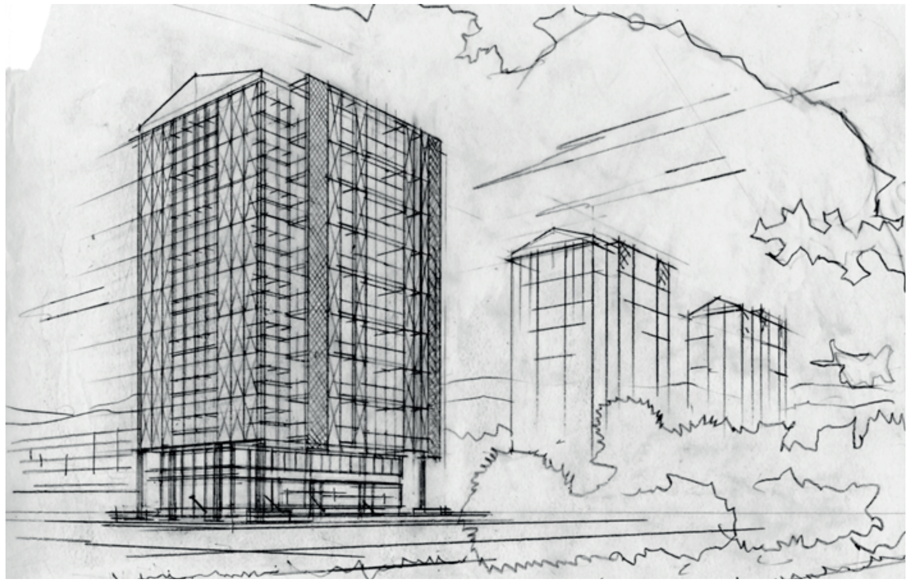
Mark (Figure 01) and details of the single buildings, based on the urban block subdivision.

In evidence, the building in Via Castelgomberto 35, case study for the retrofit proposal.

«Ufficialmente siamo "a posto" come progetto, ma per contro siamo scontentissimi di fronte a noi stessi e perciò, moralmente, di fronte all'Istituto. Con Questo progetto non facciamo che perpetuare i sia pure inevitabili errori commessi anni or sono con le "disposizioni INA" nella prima fase delle sue realizzazioni. Dico inveitabilmente in quanto allora era già grande cosa, di fronte all'estero, organizzare comunque una così importante opera di ricostruzione, andando in scena senza prove. Di fronte alle imprescindibili esigenze economiche, al profile tecnico ed estetico purtroppo, le realizzazioni sono quelle che sono: "serbatoi per famiglie".

Nella attuale fase di realizzazione non stiamo tenendo nessun conto della esperienza precedente e continuiamo ancora a costruire con i sistemi che poco differiscono da quelli che vediamo usati nelle case collettive [..] dei tempi di Roma.»

[PoliTo, Archivi biblioteca Roberto Gabetti, Fondo Carlo Mollino, ACM_PdV11, Lettera 16 giugno 1957]



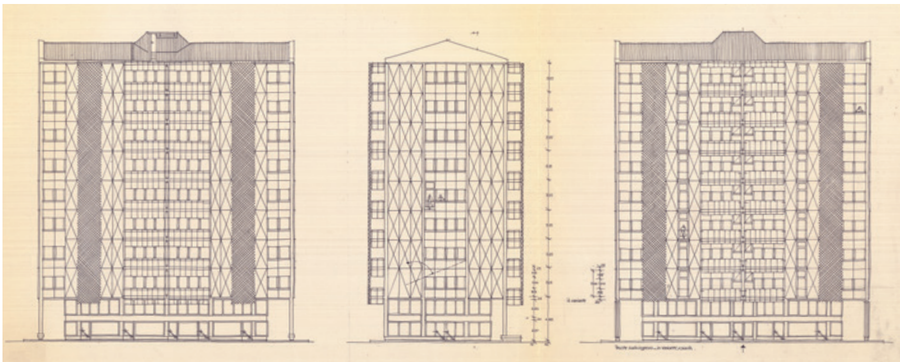


Figure 04
(Above)

Perspective study for a design option (1958)

Original drawing, pencil and pen on paper.

Figure 05
(Middle)

Perspective study for a design option (1958)

Original drawing, pencil and pen on paper.

This second drawing shows a gradual approximation to the final, constructed design proposal.

Figure 06
(Below)

Study for the prefabrication of elements (1958)

Original drawing, pencil and pen on paper.

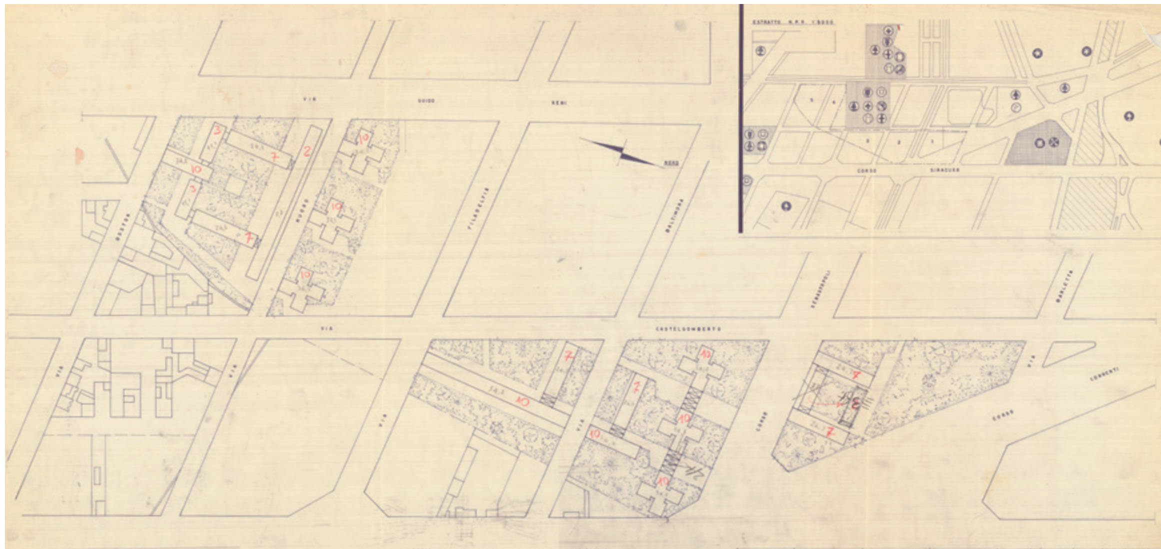
This study drawing, for the elevation of the solution portrayed in Figure 05.

The drawings from the Archive dedicated to Carlo Mollino show the relentless research for a modular coordination of the elements of the facade and of the structure, to allow for their prefabrication and serial assemblage on the building site.

Figure 07
(Next page, above)

General plan, layout of a different proposal for the INA-Casa development (1958)

Original drawing, pencil and pen on paper.



The design proposals differed for two main aspects: first, different urban layouts were proposed. One of them provided buildings aligned with the axes of east-west direction streets (such as Corso Sebastopoli, via Baltimora, via Filadelfia and via Nuoro), denying the non-orthogonal vector of via Castelgomberto that cuts through the whole site. The original drawings show a very different configuration in plan, with fewer, cross-shaped, 10 storeys towers and long low to mid-rise long blocks (with three different heights: 3, 7 or 10 storeys). The buildings themselves, with some connection footbridges and terraces, shaped the whole landscape by creating vast courtyards, connected by inner streets and sidewalks in the north-south direction. The final layout is instead aligned with the north-south axes given by via Castelgomberto: four low-rise (5 storeys), linear buildings are placed in the middle of four out of the five urban blocks included in the development plan, while the 18 towers (9 storeys tall), aligned on the same street axes, were displaced along the urban blocks' fringes. This plan included two additional towers on the northern end of the first lot (wedged between Corso Correnti and via Castelgomberto, property of INCIS), stores in the towers' ground floors (particularly when directly prominent the boundary streets), though with no additional common services and infrastructures, besides the thermal power plant facing via Castelgomberto (in the third urban block). However, generous fenced green areas and common open spaces had been left in the resulting spaces between the towers and low-rise buildings. **(Pace, 2010)**

The whole urban-scale conceptual stage happened within the context of the (back than) recent *PRG* (city's general master plan),[03] which established Turin's road and urban layout for the entire reconstruction and industrial era of the city. The typical zoning approach of this master plan contributed to the large scale process of urbanization, defining a cultural historic centre to be rigidly preserved and vast suburban areas (former farmlands) for popular and speculative residential developments.

[03] D.P.R. 8 ottobre 1955, n.1515, in materia di "*Varianti al piano regolatore edilizio di ampliamento della parte piana ed al piano della zona collinare della città di Torino.*"

The *PRG* (*Piano Regolatore Generale*) was approved by the city's administration on April 7th, 1956. A presentation of the whole master plan can be retrieved from:

Viotto, P. (1956). *Lineamenti del Piano Regolatore Generale della Città di Torino.* ATTI E RASSEGNA TECNICA della Società degli Ingegneri ed Architetti in Torino, 10(7), pp.229-288.

Figure 08
(This page, left)

Turin's PRG functional zoning (1956)

Zoning: definition of residential areas and their densities (Tav. 5)

In red, the area of the Corso Sebastopoli neighbourhood, part of the Mirafiori Nord district, defined as a potential residential zone in the master plan, with an allowed maximum density of 330 inhabitants/hectare and a possible construction volume of 5 m^3/m^2.

Figure 09
(Next page, above)

View of the newly built quarter (early 60s)

However, a second relevant thread led the design team in their choices, in particular regarding those at the scale of the building. As evidenced by the radical position assumed by Carlo Mollino regarding the issue of mass housing development, the topic of the industrialization of the construction process became a crucial concern for the designers. Francesco Dolza, son of a well known city's contractor of the previous generation (the engineer Giuseppe Dolza), as a hybrid professional between a designer and an entrepreneur, managed to experiment, in this occasion, his great interest for processes of productive rationalisation, an attention that came from the family's construction company and that he would have developed in more depth in the following decades. **(Gibello and Sudano, 2002)** Most of his forward-looking ideas proofed, however, ahead of times, as the realisation of the Corso Sebastopoli neighbourhood can testify. The final, built version of the project does not contain most of the attempts of the involved designers to go beyond the traditional construction site praxis (as shown in the original drawings), towards the integration of standardisation and prefabrication means. Construction costs arose to over 2.250.000.000L for a total of 816 dwellings, while for the *Falchera* neighbourhood, only a few years earlier, it was possible to produce 917 apartments with an investment slightly higher than 1 billion and a half. **(Pace, 2010)**

[04] Another large scale *INA-Casa* development in Turin's north end, built in the first half of the 50s and settled in the district of Falchera.

[05] R.D. 28 aprile 1938, n.1165, in materia di "*Approvazione del testo unico delle disposizioni sull'edilizia popolare ed economica.*"

[06] Promoter of the: L. 31 maggio 1903, n.254, in materia di "*Istituto Case Popolari*"

La città pubblica: first life of a *INA-Casa* neighbourhood

The *INA-Casa* plan gave birth to the most relevant experience of public housing development in the Italian history, and so it remained ever since. It was a moment in which the state itself became the main promoter of urban development, in a general enthusiastic approach towards progress: entire new landscapes arose in a short time frame outside of the historic and cultural centres of the Italian major cities, in and around the biggest plants and factories of the first age of industrialization. A "public city" (*città pubblica*), synonym of a reformism that, motivated also by the necessity of a physical and social reconstruction of the city after the Second World War's disruptions, seems nowadays all too far from the current models of evolution and transformation of the city. **(Di Biagi, 2010)** Promoter of this development in the Corso Sebastopoli neighbourhood was the IACP (*Istituto Autonomo Case Popolari*),[05] meant to realise new interventions and manage the national public housing estate. A public body born from the ashes of a previous experience, the ICP (*Istituto Case Popolari*), created by the deputy Luigi Luzzati[06] at the beginning of the XX century to give an answer to the housing shortage, in particular regarding the city of Rome. The program, however, gained wide popularity and consent all over Italy: within a decade, sections of IACP had opened in Naples, Venice, Treviso, Varese and many other cities, from north to south. The birth of this body in the city of Turin dates back to 1907, and it contributed ever since to the development of the residential public estate. The institute preserved this important role, eventually with renewed potential, during the post-war reconstruction era:

IACP was acting as a promoter and contracting authority for both private developers (namely the biggest industrial companies of that time, FIAT in first place) and state financed programs. **(IACP Torino, 1967)**

These developments became often the ground for a heated debate and the radical experimentation of architects and planners, facing the momentous task of transferring the new social and political orders and ideals into material traces on previously unexplored territories. **(Di Biagi, 2010)** The persitance of these post-war neighbourhoods is a tangible physical trace of the abstract structures of living space promoted by the designers and intellectuals at that time, whether it is about the interior space of dwellings or the exterior areas, the non-built collective space in between. The entire *INA-Casa* plan produced a total of 355.000 dwellings, about the 10% of those built in total within the same time frame, involving about 17.000 professionals. **(Di Giorgio, 2011)** This is only one of the peculiar aspects of the *Piano Fanfani* experience. It became the chance for a whole generation of planners, architects and engineers to confront with the topic of public and popular housing, and to take action with relative ease. Second, the efficacy of the information and technical coordination method adopted since the very beginning, still with a remarkable morphological and typological variety of results: the *INA-Casa* management made use of design manuals, booklets carrying norms and regulations to instruct the involved professionals about minimum standards and good design praxis. **(Carfagna, 2012)** The first booklet[07] was published only two months after the founding law, and it fully embodies the prescriptive nature of these manuals. It provided normalised plan layouts, sorted by different building's typology (i.e. multistorey, low-rise, terraced house). These layouts were also divided by the rooms' number of apartments, indeed the most restrictive measure contained in the booklets. For the first seven years, these rules provided four different possible sizes: 30, 45, 60, 75 and 90m^2. The rather small dimension of dwellings of this first stage of the *INA-Casa* is strictly connected to the housing shortage of the early 50s, tragic consequence of the Second World War's disruptions. These parameters had in fact been updated within the second stage of the *Piano Fanfani*, with the values of 50, 70, 90 and 110m^2. **(Di Giorgio, 2011)**

It is remarkable of the cultural approach the fact that architects, at that time, considered the prescriptions inherited by the modernists of the past two decades, in terms of floor plan layout, a point of perfection in the research for a rational design of dwelling's space. As the lack of photographic historical documentation about interior spaces testifies, the most relevant experimentation regarded the urban layout and the overall building types, a discourse employing the best intellectuals of this generation. Most of the debate around the interior spaces, on the other hand, was taken on by a rising generation of industrial designers: their concern was to make both liveable and mass produced the furniture and interior living spaces of the new inhabitants of the city. **(Di Giorgio, 2011)**

[07] Comitato di attuazione del piano case lavoratori (1949). *Suggerimenti, norme e schemi per la elaborazione e presentazione dei progetti: bandi dei concorsi.* Roma.

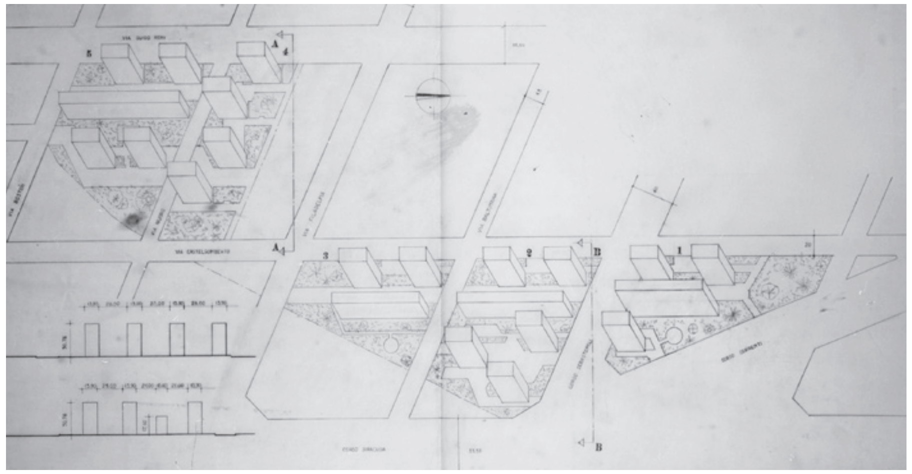


Figure 10 (Above)

View of the newly built quarter (early 60s)

Figure 11 (Right)

General plan, with volumes of buildings (1958)

Original drawing, pencil and pen on paper.

The second manual,[08] published in 1950, is the first to include a number of realised *INA-Casa* projects, as demonstrative case studies for an adequate arrangement of the new settlements, in particular in historical centres or in rough landscapes. This second booklet gave a clear direction to architects involved in the general conception of popular housing quarters, towards the dictates of an expansive, low density urban planning. Two objectives are raised as crucial paradigms of the design for the living space: physical and moral health. The first, regarding in fact humans' physiology: planners had to provide enough light and air, together with proper vegetation areas and unobstructed views, allowing for the physical and mental wellness of the inhabitants. The latter, instead, implying the psychological and social side: it was widely acknowledged that these new towns were prone to experience social frictions and degradation. However, the uniqueness of this approach did not reside in its objective, rather in the answer itself, so to connect social and health issues to a set of few urban density parameters. On the one hand, architects and planners were empowered beyond their limits with the social responsibility of bringing quality to the workers' residential environment, though the expansive urbanism imperative did not always produce the expected outcomes. On the other hand, the project of open spaces became a compelling concern for an entire generation of architects and planners, as fundamental quality parameter of dwelling. It is with this

[08] Comitato di attuazione del piano case lavoratori (1949). *Suggerimenti, esempi e norme per la progettazione urbanistica: progetti tipo.* Roma.

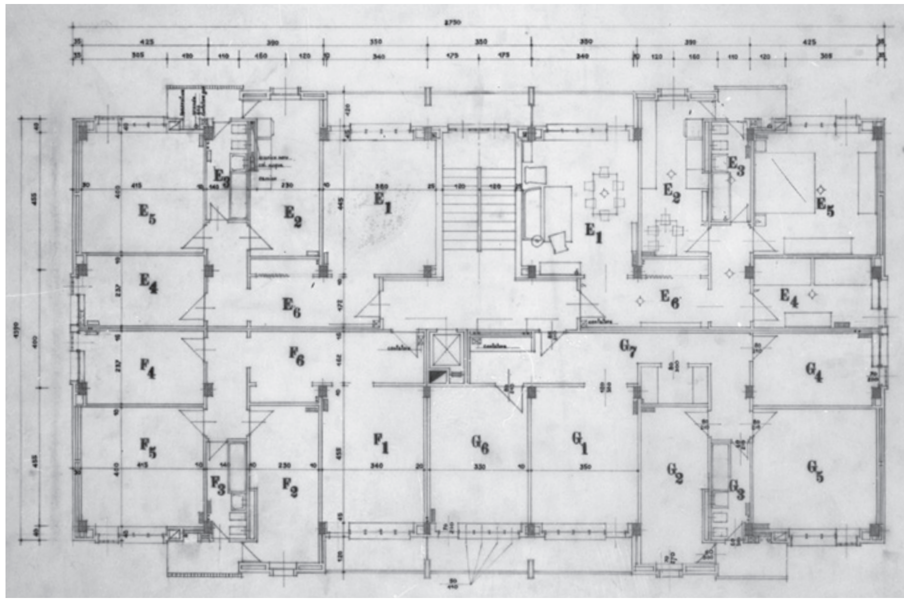
aspect in mind, rather than that of the design of dwelling units themselves, that the professionals approached all too often the design of public housing new towns and neighbourhoods, thought giving birth to a proficient debate on the quality and liveability of the modern city. (Carfagna, 2012) All of this happened within the context of a cultural approach peculiar of the XX century, which considered urban planning as a way to translate a social and political utopia in the real world. To the historic city, a collective structure in which buildings are double sided objects, shaped by a number of social relations and rules, is radically opposed a modern city, the manifestation of a strong need for ideal purity, in which anything contextual is to be considered as a contaminant. The birth of the notion of free standing objects in an idealised, neutral space: a city made of voids. (Rowe and Koetter, 1978) Accordingly, the great attention given to the topic of new residential suburbs shifted away for decades the debate from the care for historic city centres, being radically condemned as all too densely built and inhabited, with severe consequences for their preservation. (De Fusco, 1999)

The *Corso Sebastopoli* neighbourhood embodies, at different extents, all of these aspects: a new town, settled on a vacant lot, made of sparse objects connected by a vehicular network, which, in turn, had just colonised with its rational grid and hierarchy this abstractly pure and immaculate terrain. The organisation of the building's typologies is hierarchically connected to the distribution's layout of the overall complex. To each part of this arrangement, a letter is assigned (from A to D, as shown in Figure 01) corresponding to the different stairwell blocks, arranged along the inner streets and walkways in the north-south direction, responding to the necessity of a maximum supply of daylight and natural air through the whole site. Stairwells of both towers and linear block have been provided with elevators. The apartments' plans are constrained to this general order: in turn, a letter is assigned to each of the plan's configurations. Their regular, repetitive layout demonstrate the strict observance to the prescriptions of the *INA-Casa* booklets. For instance, the towers (blocks A of the general layout) provide 4 apartments at each storey with three different configurations (E to G, in Figure 12) and two sizes ($75m^2$ for the 5 rooms units, $90m^2$ for the 6 rooms ones). All of the 816 dwellings were provided with one single bathroom and separate kitchen and living rooms. Living and sleeping areas are organised symmetrically, according to the heliothermic axis method, as specified by the manuals. All of the residents had access to a separate cellar in the basement (as an additional storage space) and to a rubbish collection shaft. (Libert, 2017) If nothing more than the necessary was left to the common spaces within the building's perimeter, the opposite approach was employed for the left-over voids between the blocks. Each urban block is treated as a neutral, empty spaces filled with abundant greenery and vegetation, with the only exception of the inner paths and buildings. Fenced at the perimeter and permeable only through the access of the inner roads, these voids were in truth the collective space of the newly built quarter.

Figure 11 (Right)

Typical floor plan of a residential tower (A) (1958)

Original drawing, pencil and pen on paper.



[09] L. 14 febbraio 1963, n.60, in materia di "*Liquidazione del patrimonio della gestione Ina-Casa e istituzione di un programma decennale di costruzione di alloggi per lavoratori.*"

A recent collection of personal memories of some of the first inhabitants of the *Corso Sebastopoli* neighbourhood, in occasion of the 60th year of life of this quarter since its conception, (Libert, 2017) evidenced the atypical living conditions of these new towns. A hybrid situation between urban and rural lifestyles, especially within the first years, when the young quarter was a sort of a satellite city, yet to be surrounded by the urban development, and the workers who had just moved in were still used to the conditions of the small towns and farmlands. However, the good architectural quality of this *INA-Casa* realisation and the generous amount of freedom left by design in the definition of collective open spaces owns a great value to most of the interviewed residents. Also, the initial shortage of services for the inhabitants and the lack of connections to the rest of the city and to infrastructures is a consistent part of many of the reported memories, though with alternate moods, as well as the great demographical diversity of the inhabitants, which inevitably shaped their growth.

However, despite its overall success, the *INA-Casa* era lasted only 14 years, until 1963.[09] A new plan, named PEEP (*Piano Edilizia Economica e Popolare*) had been provided by the central government to support the development of the affordable stock on the country's territory. The categories of private affordable housing and public popular housing developments merged, envisioning an ever-growing collective effort of both public sector and private developers in the urban transformation processes. For, if much of the criticism regarding to the INA-Casa era was due to a lack of involvement of regional power in the decisional process and to the unexpected mechanisms of out of control rise of land revenues, local administrations had been empowered. Additionally, the new body GESCAL (*GEStione CAse per i Lavoratori*) took charge for the administration of the entire *INA-Casa* real estate and assets. (Di Giorgio, 2011)

La città contemporanea: afterlife of a *INA-Casa* neighbourhood

The conclusion of the *INA-Casa* plan marked the beginning of a new era for the architectural and political debate on the topic of public and popular housing. The urban and architectural approach shifted towards the development of large scale architectural complexes, characterised by the high density of dwellings and able, at least in their intention, to incorporate all of the necessary urban functions and services. Concurrently, the heavy prefabrication and large scale industrialization of building components became a pivotal element in the production of popular housing. A new, unified dimension of urbanism, architecture, construction and politics was sought; though, yet again, the positive intentions to overcome the social issues that had emerged after the first season did not produce any relevant result, rather some of these eventually got worse. Some peculiar realisations of this epoch are the well known residential complexes *Corviale* (Rome) and *le Vele* (Naples), and some new entire residential districts, as the *Zen* in Palermo: all of which manifested serious social and physical decay phenomenon within a few years after their construction. The debate on the topic of public housing is gradually influenced by the aftermath of these failed developments, poisoned by the ever more pervasive diffusion of corruption episodes, finally leading to the disrepute of the public opinion on this regard of the last decades. (Di Giorgio, 2011)

The methods of administration used by the new institute GESCAL were all in all similar to those employed by the INA-Casa management: the contracts did not change, in particular the future sale agreement clause. For this reason, the apartments realised by the *Piano Fanfani*, once public owned estate, are now almost entirely private property, and indeed those of the *Corso Sebastopoli* neighbourhood. Hence, the novelties introduced by the new 1963 10-years plan did not affect the residents, at least in the short term. However, the subsequent events of the GESCAL management era testify a general decay of the public administration of this and similar popular housing developments. Besides the treasury and assets inherited from the INA-Casa, the most consistent part of the founds available to the new public body came from withholding taxes, retained from the employees' salaries. For, if GESCAL's treasury arose, within the decades, to the astonishing amount of 20.000bnL (in 1994), a consistent amount of this founds was not employed for its objectives, popular housing stock management and improvement, rather to make up for the ever growing difficulties of the country's public finance. Furthermore, the complex overlaps of local, regional and national responsibilities discouraged all too often the use of this treasury for the purpose of public housing, with the risk of wasting them in the multiple folds of an all too entangled system. (Cirillo, 1996) The contributions were abolished between January 1st 1996 (the component dependent on the employee) and December 31st 1998 (regarding the component dependant on the employer). (Gescal, 2019)

At the turn of the century, much of the interests of the public sector in popular housing is deprecated. On the one hand, given the crisis of public institutes for the development of such programs and management of the (still) public housing stock, it was clear that these bodies, in order to be effective, had to operate as private enterprises in a completely renewed building industry and housing market sector. Also, the last lines of the GESCAL management had shown that the era of massive funding policies by the central government was definitely over. Hence, a new rearrangement of the competencies of national and regional powers had been approved in 1998,[10] which defined their competencies until nowadays: to the government, the definition of general objectives and standards for the public affordable housing developments and assignation of the dwelling units. A direct involvement is to be expected only in projects of national relevance, whilst for the rest of cases, all of the responsibilities are on the back of regions and local administrations. (Di Giorgio, 2011) In Turin, explanatory of this process was the foundation of ATC (*Agenzia Territoriale per la Casa*),[11] which in 1993 took over the IACP. This latter, all through the 80s and at the beginning of the 90s, had undergone some serious financial woes, due to the considerable amount of housing stock under its control (which led to two episodes of receivership). (MuseoTorino, 2019) The ATC is a public service institution, non-economic, auxiliary of the Region, endowed with organizational, patrimonial, administrative, accounting autonomy. It implements and manages the social housing stock. Its functions are, at present times, defined by the last regional law in the field of social housing, dating back to 2010,[12] exercised with competences extended to its respective territorial area. (ATC Torino, 2019)

Currently, the definition of subsidised housing (as the traditional popular housing of the *INA-Casa*) is deprecated: the number of interventions in which local authorities or the State are totally responsible for the construction and its subsidy are very few, if not absent, nor it is expectable for this trend to revert in the future. It has in recent times developed, on the other hand, the trend of Social Housing, or initiatives led by private developers and contractors, though within some sort of agreement and facilitation with the public authority in charge. Its objectives are the same, to resolve the shortage of affordable dwellings, though making up for the inability of the public sector to take on this problem without actually replacing it. Rather it proposes an alternative suitable also for a growing trend of people that, although being outside of the common requirements to receive an apartment in a popular housing context, is also outside of the target imposed by the market, especially since, in recent times, the rental prices in most of the major cities have risen consistently. Furthermore, a couple of perspectives are noteworthy: Social Housing initiatives are particularly promising in contexts where the public sector cannot afford consistent investments in the development of the residential stock (as it is the case of Italy and Turin), and the connection with the issue of obsolete or dismissed

[10] D.L. 31 marzo 1998, n.112, in materia di "*Conferimento di funzioni e compiti amministrativi dello Stato alle regioni ed agli enti locali, in attuazione del capo I della legge 15 marzo 1997, n. 59.*"
In particular: Sezione III - Edilizia residenziale pubblica

[11] L.R. 26 aprile 1993, n.11, in materia di "*Nuovo ordinamento degli Enti operanti nel settore dell'edilizia residenziale pubblica sovvenzionata. Abrogazione legge regionale 16 dicembre 1987, n. 65.*"

[12] L.R. 17 febbraio 2010, n.3, in materia di "*Norme in materia di edilizia sociale.*"

existing constructions. (Delera, 2017) In particular, if we consider that the aging *INA-Casa* heritage will soon need a serious maintenance program, the recent experience of Social Housing developments might come at hand. The obsolescence is functional in first place: the typologies offered by these dwellings are often out of the actual standards of the rental market, now very often oriented towards small families, single persons or particular categories (such as students or temporary residents). The lack of common spaces and functional equipment is also a reality of many case studies. Furthermore, a rapid technological and structural deterioration grew along with the privatisation of the stock and the vanishing of a management body, damaging at the same time both the possibility of a revenue for the public sector, and that of the now private assets at the same time (and expectedly growing costs for their repair and maintenance in the forthcoming years). (Marchi et al., 2017) The old dwellings respond to prescriptive design paradigms that are now totally deprecated, by virtue of a performance-based approach focused on structural safety, energy efficiency.

The possibility of an integrate intervention on the heritage of popular housing, to make up for its vulnerability and obsolescence, has been recently exploited in some research projects and speculative applications of new methodological approaches, such is the so-called Adaptive Exoskeleton. (Scuderi, 2016) The possibilities offered by the rising economy of Social Housing projects and Co-Housing strategies might become an unmissable opportunity with regard to the issue of regeneration of the existing residential stock, and in the context of a receding demand for dwellings within the traditional market environment.

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03.2 TOOLKIT: STRUCTURE

Existing construction's data

Detailed data regarding the original structure have been gathered from the original construction drawings, kept in the city archives. These report the basic informations about the overall geometry of the artefact, as well as the detailed informations about the frame's structural elements, including the prescription of materials and reinforcement of beams, columns and slabs.

The relevant drawings and information have been organised in:

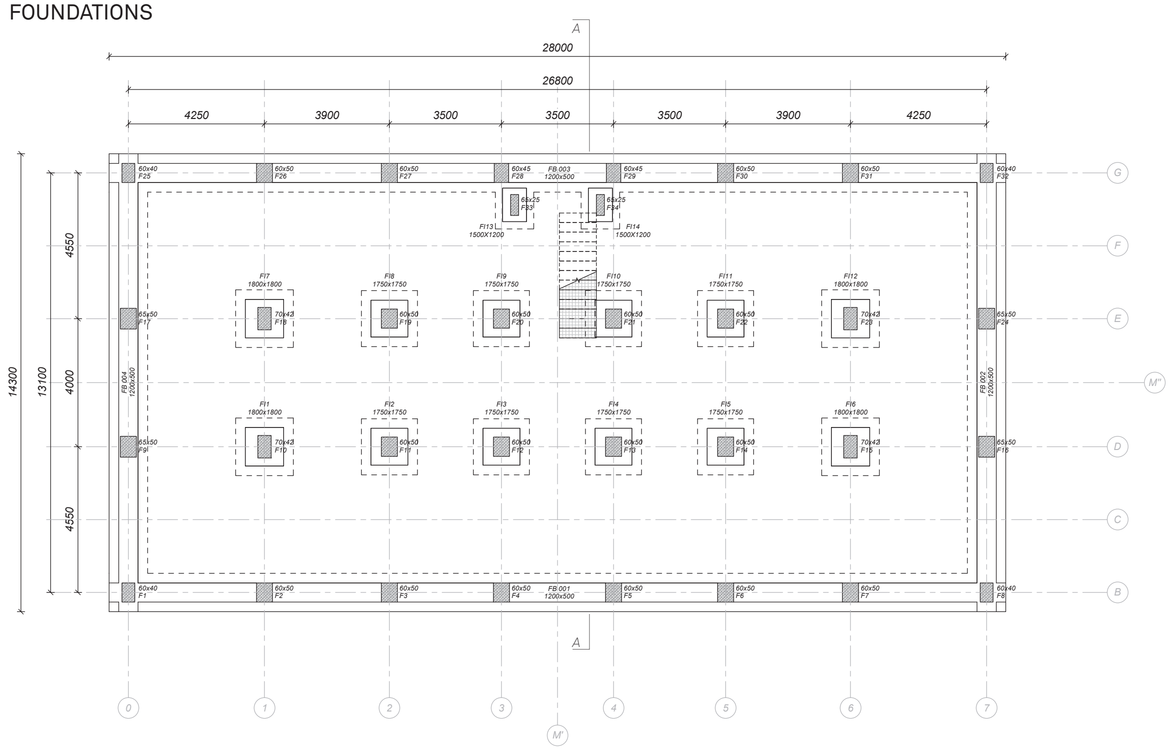
- Structural plans
- Structural sections
- Detailed sections
- Columns details
- Beams/Slabs details
- Foundations details

Besides the information included in the original project's documentation, the direct observation of the building provided useful informations about the actual state of conservation: the presence of consistent modifications to the original structural configuration is excluded and the rather decent state of preservation of the exterior components of the envelope lets assume that also the reinforced concrete structure, not exposed, lies in a healthy condition. However, some phenomena of decay are notable in the exposed cantilevered slabs of the balconies on the east and west facade. The original drawings showcase the deficiency of the original constructional details in comparison with the actual prescriptions of the design code in terms of seismic resistance, in particular the absence of enhanced reinforcements in the critical areas around the nodes between columns and beams, and the slender dimension of beams manifest an evident lack of seismic safety.

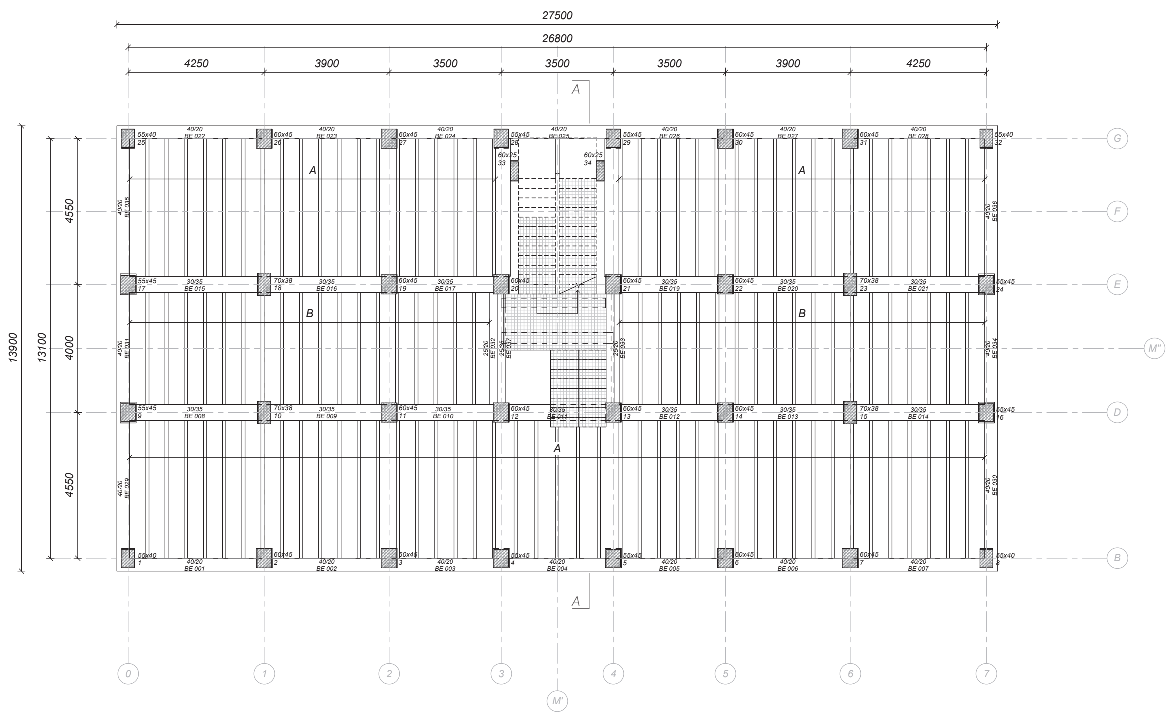
The absence of direct in-situ testing and of direct surveys place the degree of knowledge of the structure in the Knowledge Level 1 category. With particular regard to the properties of concrete materials and the steel of reinforcing bars, the prescriptions contained in the original documentation have been confronted with the structural design code in force at the time of construction.[01] These report the minimum requirements of strength for the materials that are prescribed in the original drawings. The combination of these data and of the considerations in the initial study of the structural issues of this building led to most of the design choices in terms of further structural modelling and analysis.

[01] D.L. 16 novembre 1939, n.2229, in materia di "*Norme per l'esecuzione delle opere in conglomerato cementizio semplice od armato.*"

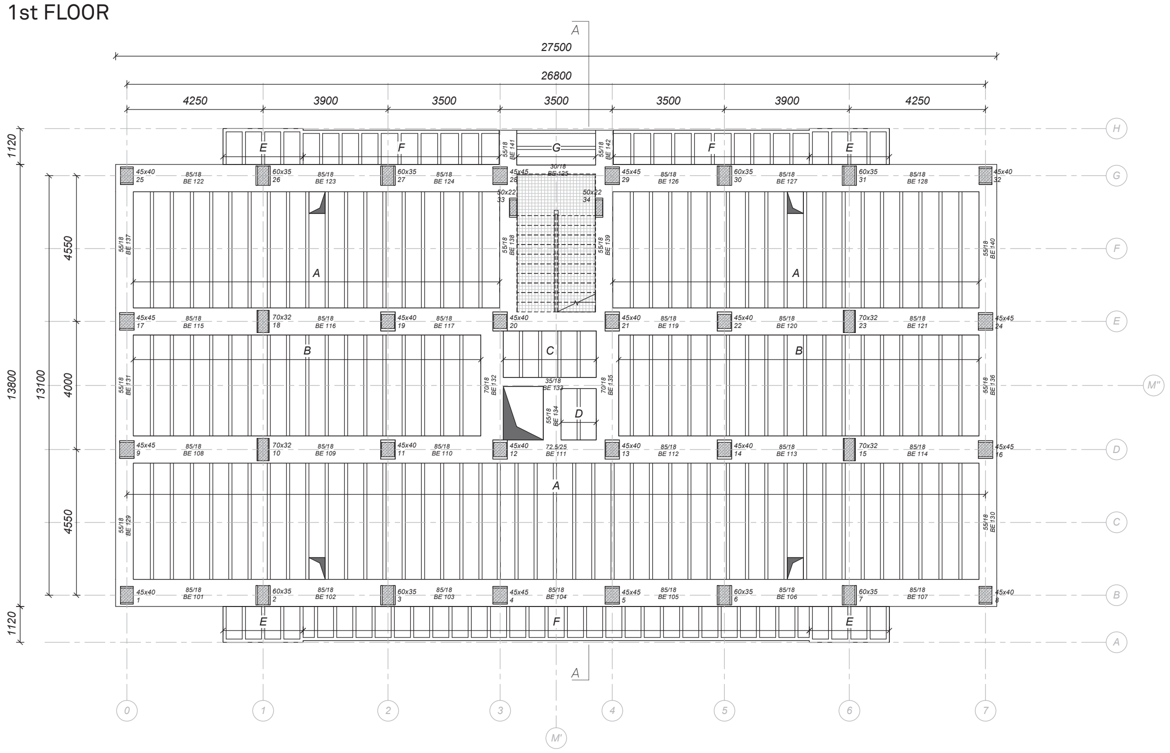
Structural plan
FOUNDATIONS



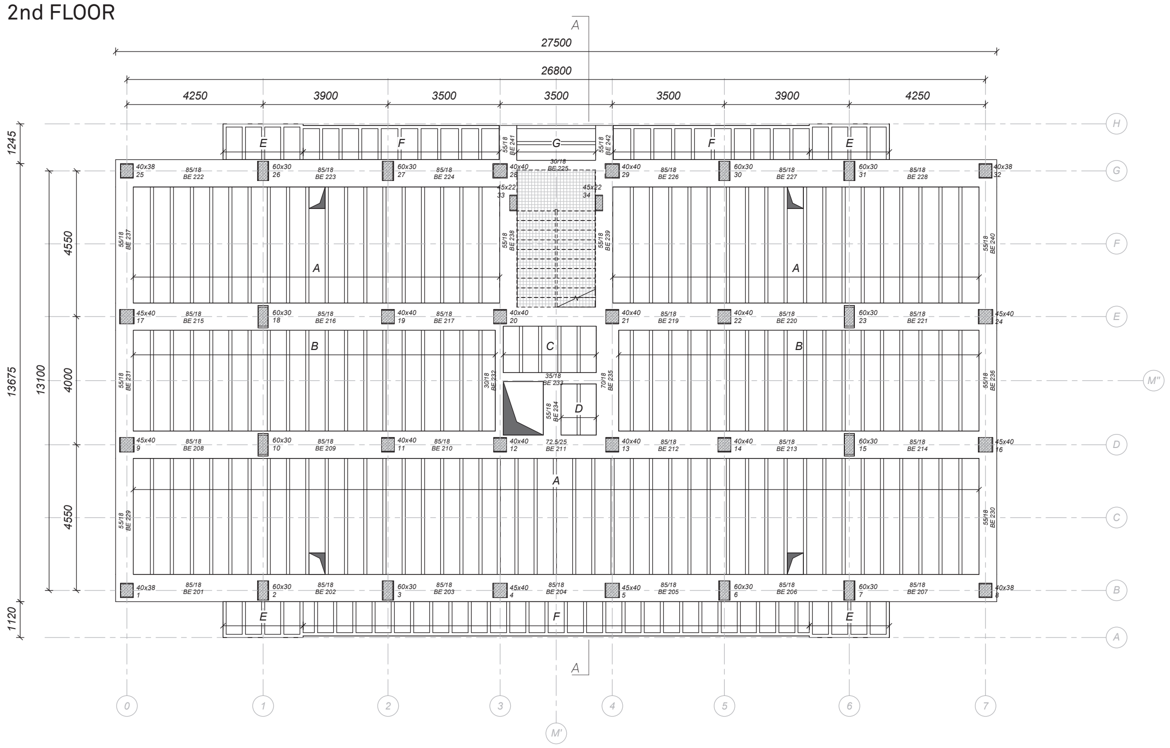
Structural plan
GROUND FLOOR



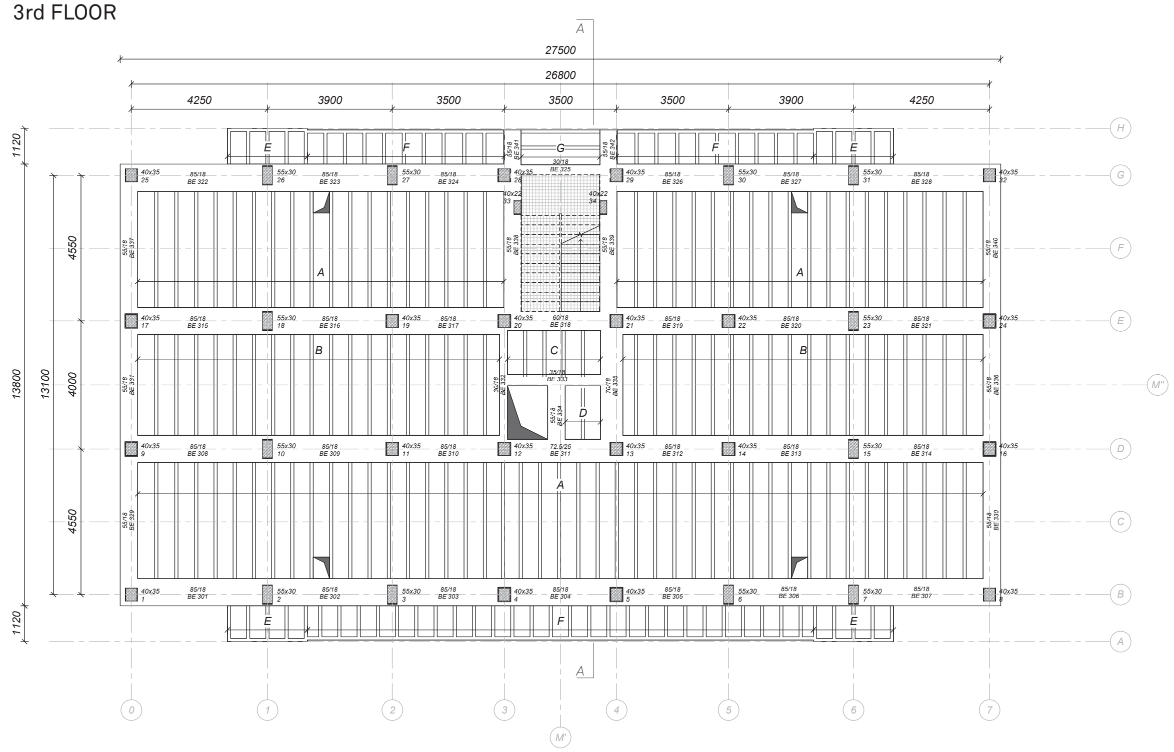
Structural plan
1st FLOOR



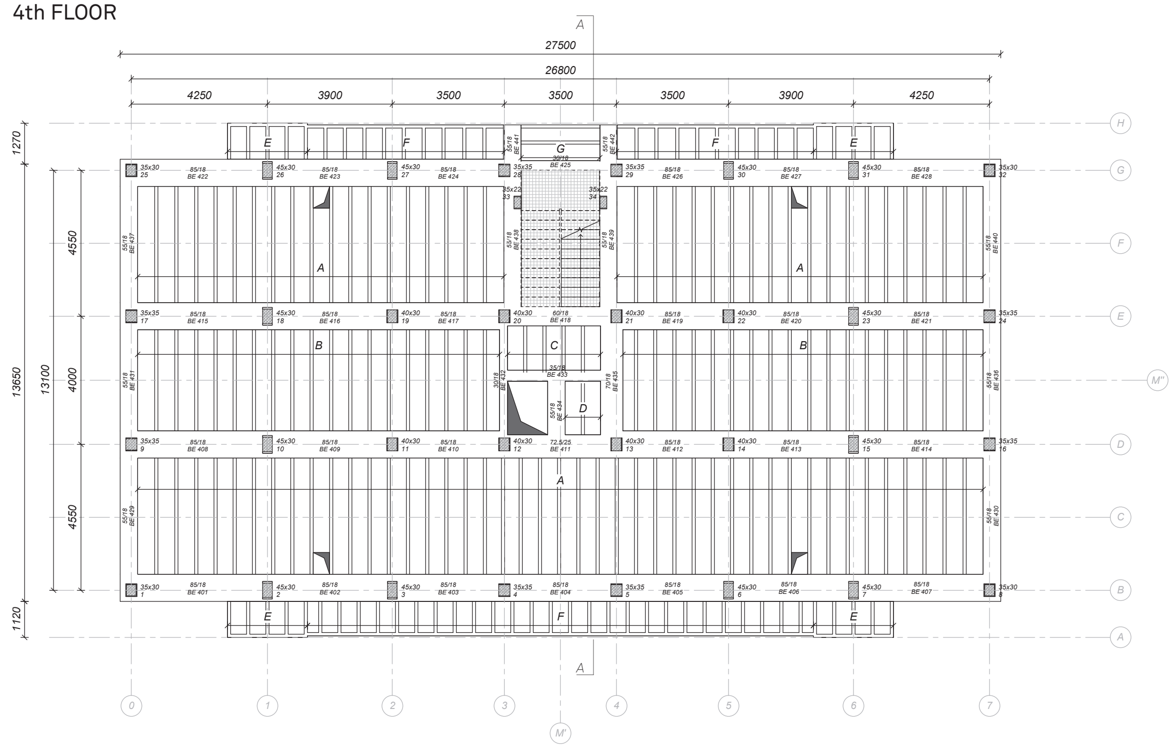
Structural plan
2nd FLOOR



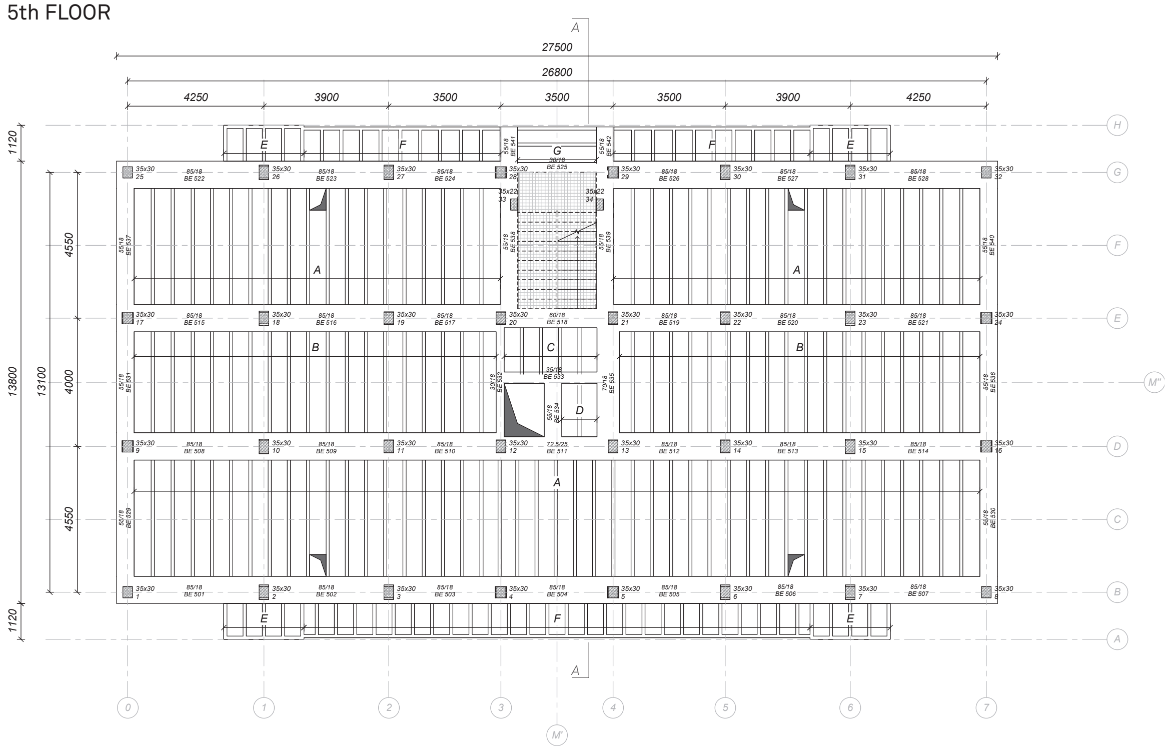
Structural plan
3rd FLOOR



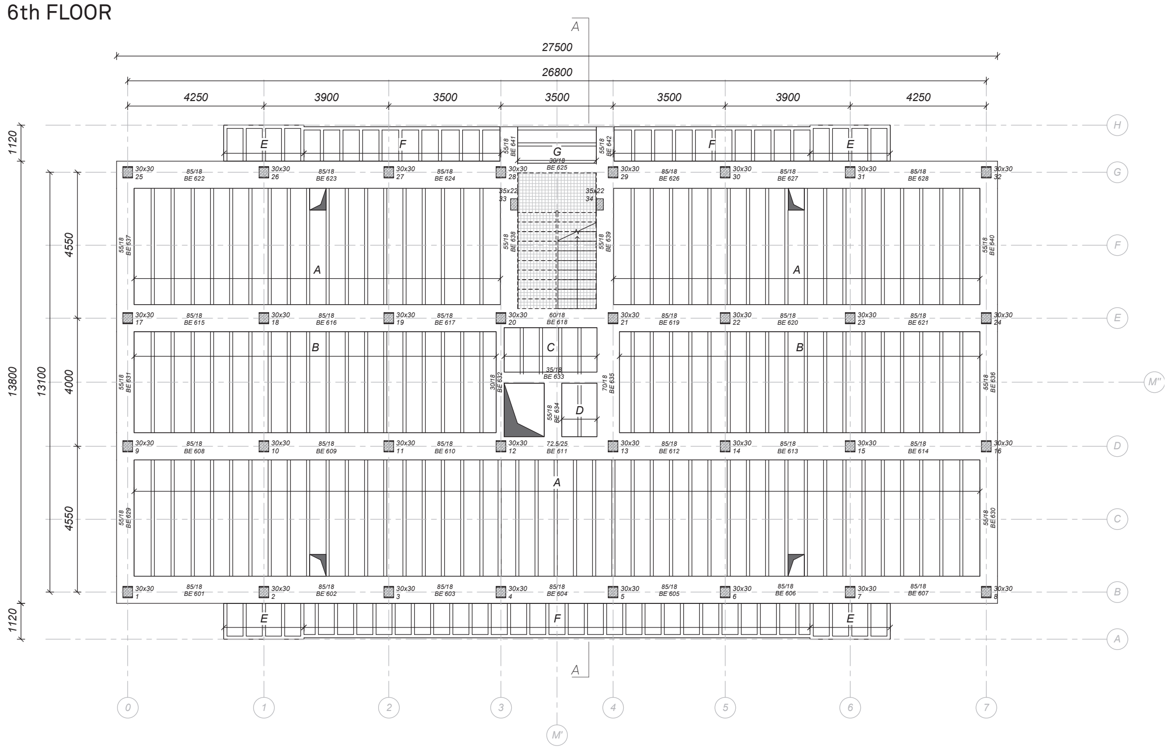
Structural plan
4th FLOOR



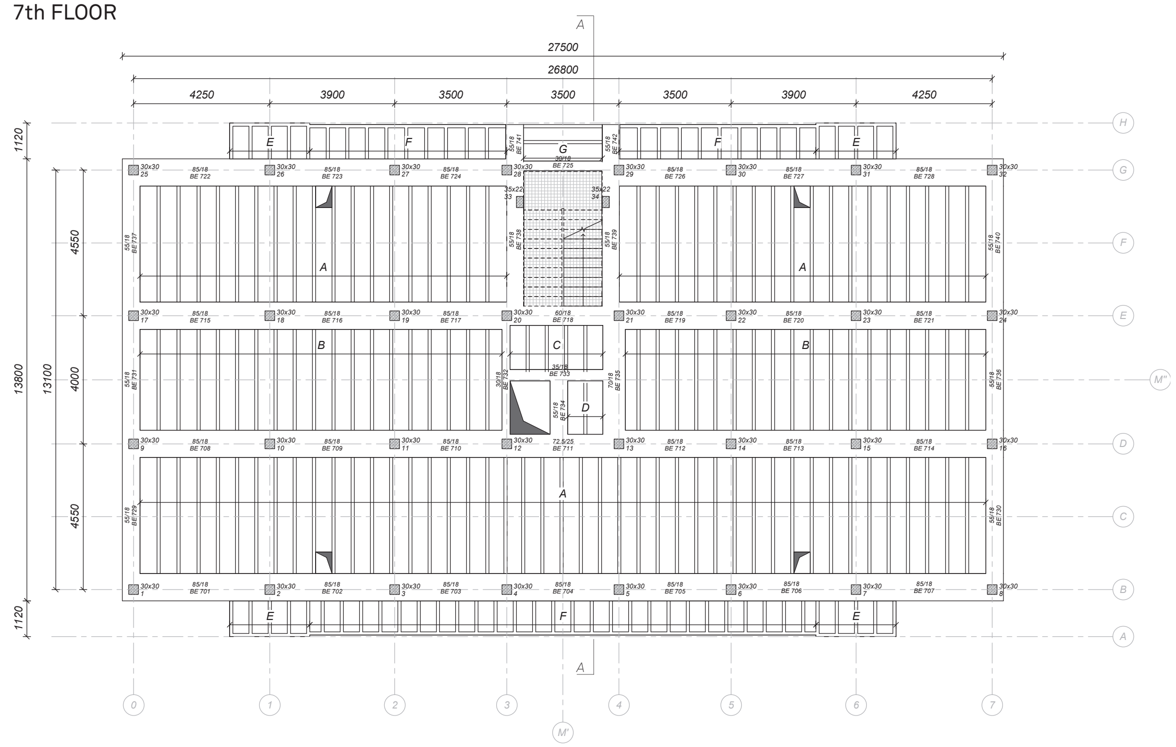
Structural plan
5th FLOOR



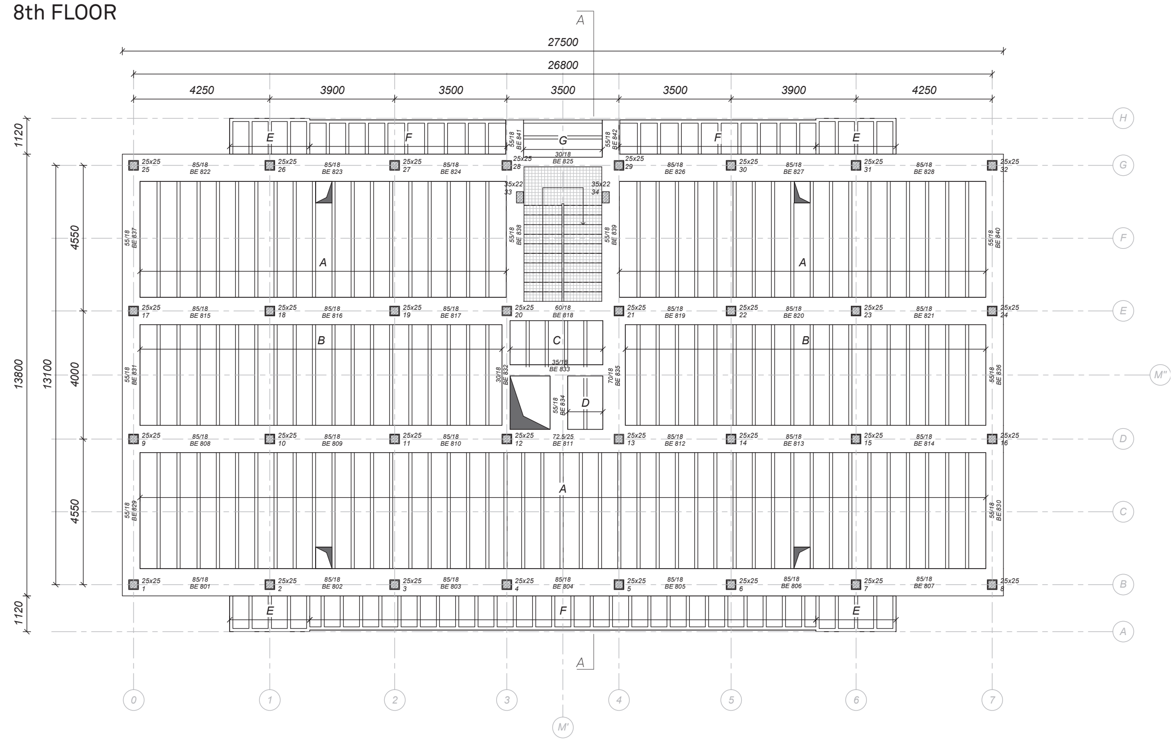
Structural plan
6th FLOOR



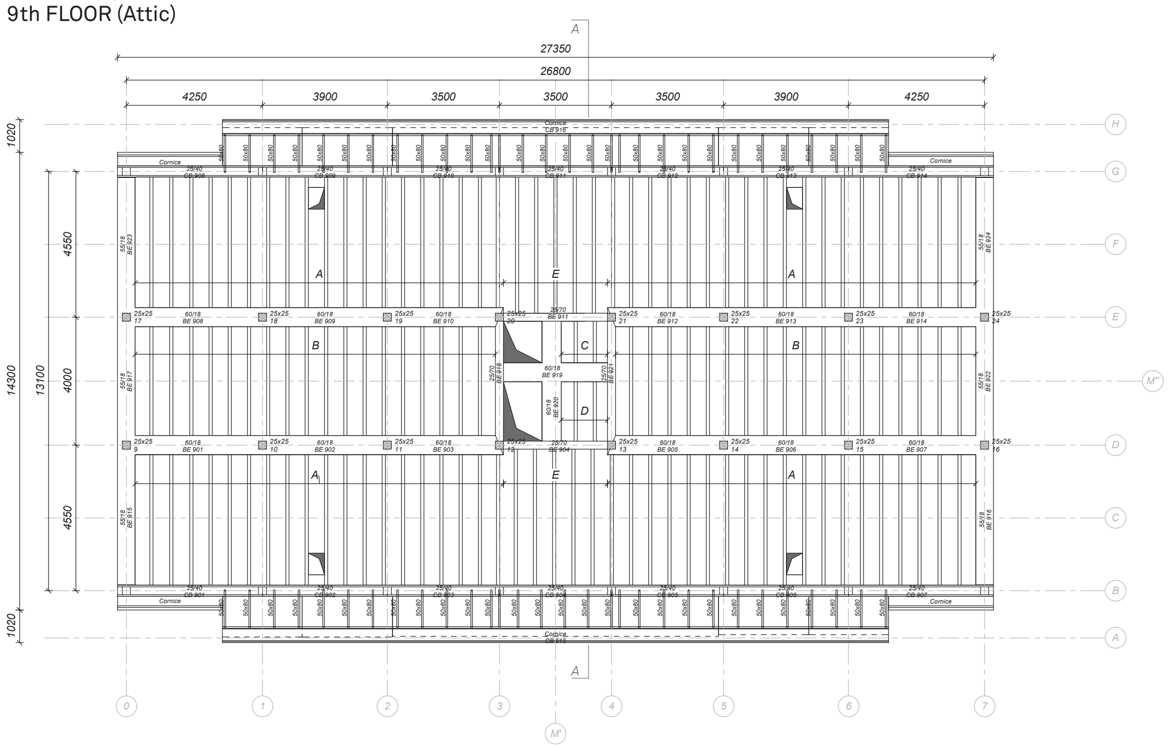
Structural plan
7th FLOOR



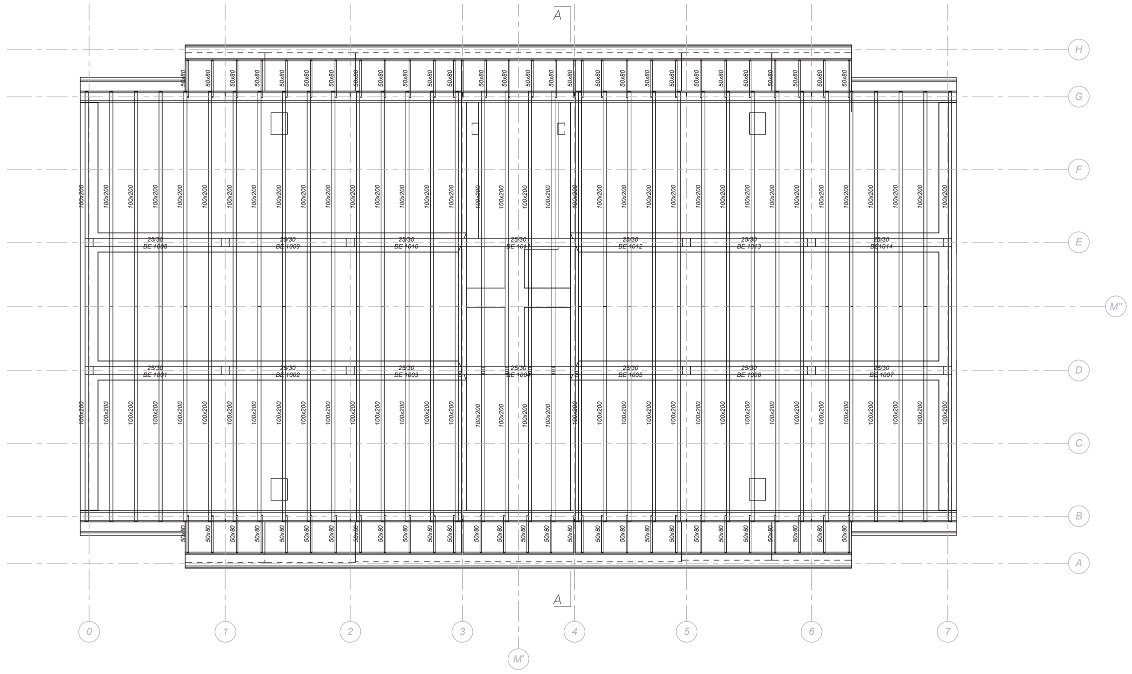
Structural plan
8th FLOOR



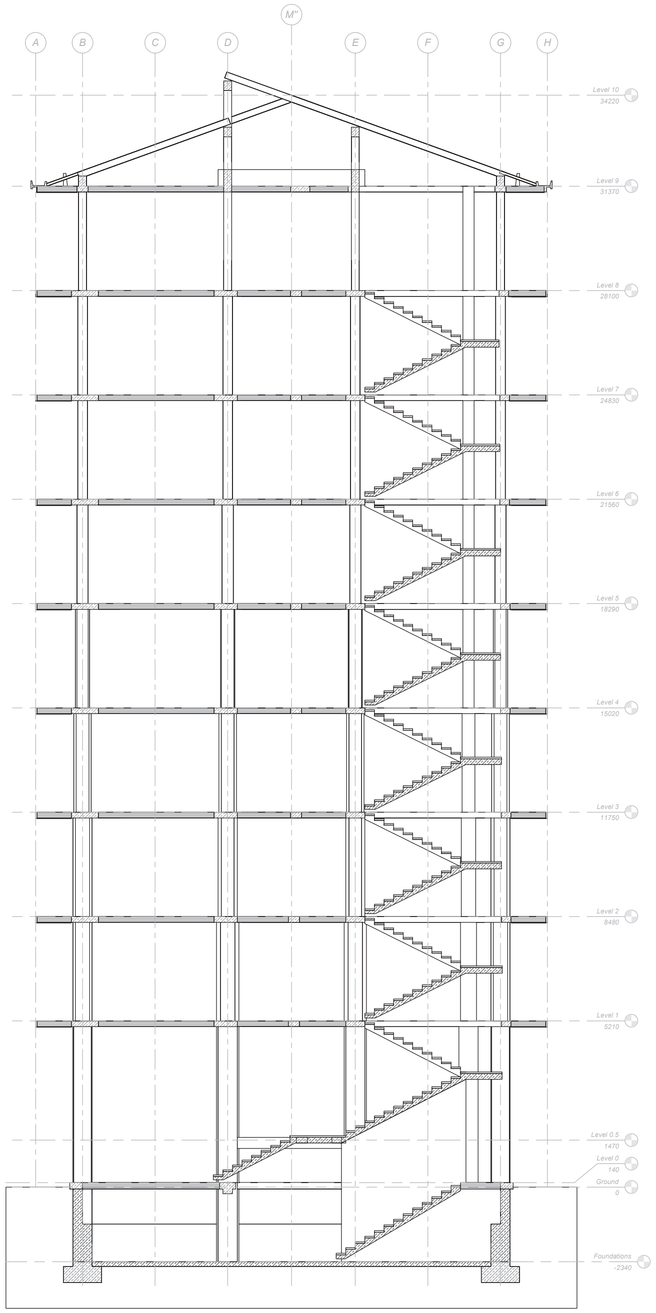
Structural plan
9th FLOOR (Attic)



Structural plan
ROOF



Structural section
SECTION AA



Construction details
RC COLUMNS

Original definition	Ground floor	1st floor	2nd floor	3rd floor	4th floor	5th floor	6th floor	7th floor	8th floor
I	70x38 4ϕ20 2ϕ14	70x32 4ϕ20 2ϕ12	60x30 4ϕ20	55x30 4ϕ18	45x30 4ϕ16	35x30 4ϕ14	30x30 4ϕ12	30x30 4ϕ10	25x25 4ϕ8
II	60x45 4ϕ20 2ϕ14	45x40 4ϕ20 2ϕ12	40x40 4ϕ20	40x35 4ϕ18	40x30 4ϕ16	35x30 4ϕ14	30x30 4ϕ12	30x30 4ϕ10	25x25 4ϕ8
III	60x45 4ϕ20 2ϕ14	60x35 4ϕ20 2ϕ12	60x30 4ϕ20	55x30 4ϕ18	45x30 4ϕ16	35x30 4ϕ14	30x30 4ϕ12	30x30 4ϕ10	25x25 4ϕ8
IV - VII	55x45 4ϕ20 2ϕ12	45x45 4ϕ20	45x40 4ϕ20	40x35 4ϕ18	35x35 4ϕ16	35x30 4ϕ14	30x30 4ϕ12	30x30 4ϕ10	25x25 4ϕ8
V	55x45 4ϕ20	45x45 4ϕ20	40x40 4ϕ18	40x35 4ϕ18	35x35 4ϕ16	35x30 4ϕ14	30x30 4ϕ12	30x30 4ϕ10	25x25 4ϕ8
VI	60x25 4ϕ20	50x22 4ϕ16	45x22 4ϕ14	40x22 4ϕ14	35x22 4ϕ12	35x22 4ϕ12	35x22 4ϕ10	35x22 4ϕ10	35x25 4ϕ8
VIII	55x40 4ϕ20	45x40 4ϕ18	40x38 4ϕ16	40x35 4ϕ16	35x30 4ϕ14	35x30 4ϕ14	30x30 4ϕ12	30x30 4ϕ10	25x25 4ϕ8

Construction details
RC BEAMS

Ground floor	Section	Model definition	Bars	Stirrups
T1	30x35	BE 008 BE 014 BE 015 BE 021	2ϕ5 1ϕ14 1ϕ14 2ϕ16	ϕ5 d: 22 cm
T2	30x35	BE 009 BE 013 BE 016 BE 020	2ϕ5 1ϕ14 1ϕ14 2ϕ16	ϕ5 d: 22 cm
T3	30x35	BE 010 BE 012 BE 017 BE 019	2ϕ5 1ϕ12 1ϕ12 2ϕ14	ϕ5 d: 22 cm
T4	30x35	BE 011	2ϕ5 1ϕ12 1ϕ12 2ϕ12	ϕ5 d: 22 cm
T5	30x20	BE 039	2ϕ5 1ϕ12 1ϕ12 2ϕ12	ϕ5 d: 25 cm
T6 inf	25x20	BE 032 BE 033	2ϕ5 1ϕ10 1ϕ10 2ϕ10	ϕ5 d: 25 cm
T6 sup	25x35	BE 037 BE 038	2ϕ5 4ϕ14 1ϕ14 1ϕ14 2ϕ14	ϕ5 d: 25 cm
T7	30x20	BE 040	2ϕ5 1ϕ10 1ϕ10 2ϕ10	ϕ5 d: 25 cm

Ground floor	Section	Model definition	Bars	Stirrups
T8	40x20	BE 002 BE 003 BE 004 BE 005 BE 006 BE 023 BE027	2ϕ5 2ϕ10	ϕ5 d: 20 cm
T9	40x20	BE 001 BE 007 BE 022 BE 028	2ϕ5 1ϕ12 1ϕ12 2ϕ12	ϕ5 d: 20 cm
T10	40x20	BE 025	2ϕ5 1ϕ12 1ϕ12 2ϕ12	ϕ5 d: 20 cm

Construction details
RC BEAMS

Typical floor	Section	Model definition	Bars	Stirrups
T101	85x18	BE 108 BE 114 BE 115 BE 121	2ϕ5 2ϕ6 1ϕ20 1ϕ20 1ϕ20 3ϕ20 2ϕ5	ϕ5 d: 22 cm
T102	85x18	BE 109 BE 113 BE 116 BE 120	2ϕ5 2ϕ6 1ϕ16 1ϕ16 2ϕ20 2ϕ18 2ϕ5	ϕ5 d: 22 cm
T103	85x18	BE 110 BE 112 BE 117 BE 119	2ϕ5 2ϕ6 1ϕ14 1ϕ14 1ϕ14 1ϕ16 2ϕ5	ϕ5 d: 22 cm
T104	72x18	BE 111	2ϕ5 2ϕ6 1ϕ12 1ϕ12 1ϕ14 2ϕ14 2ϕ5	ϕ5 d: 22 cm
T105	30x18	BE 133	2ϕ5 1ϕ6 1ϕ16 1ϕ16 2ϕ16 2ϕ5	ϕ5 d: 25 cm
T106	57x18	BE 132 BE 135	2ϕ5 1ϕ14 1ϕ14 2ϕ16	ϕ5 d: 25 cm
T107	60x18	BE 118	2ϕ5 1ϕ14 1ϕ14 2ϕ14 2ϕ14	ϕ5 d: 25 cm
T108	85x18	BE 101 BE 107 BE 122 BE 128	2ϕ8 1ϕ20 1ϕ20 1ϕ20 3ϕ20	ϕ5 d: 25 cm
T109	85x18	BE 102 BE 106 BE 123 BE 127	2ϕ8 1ϕ18 1ϕ18 2ϕ20 2ϕ18	ϕ5 d: 20 cm
T110	85x18	BE 103 BE 104 BE 105 BE 124 BE 126	2ϕ8 1ϕ16 1ϕ16 1ϕ18 1ϕ16 2ϕ16	
T110 bis	23x18	BE 125	2ϕ8 2ϕ12	ϕ5 d: 18 cm
T111	63x18	BE 138 BE 139	2ϕ8 3ϕ14	
T112	40x18	BE 129 BE 130 BE 137 BE 140	2ϕ5 1ϕ14 1ϕ14 1ϕ14 2ϕ16	ϕ5 d: 18 cm
T113	40x18	BE 131 BE 136	2ϕ5 1ϕ12 1ϕ12 1ϕ12 2ϕ12	ϕ5 d: 18 cm
T114	63x18	BE 141 BE142	2ϕ12 2ϕ10	-

9th floor	Section	Model definition	Bars	Stirrups
T201	60x18	BE 901 BE 907 BE 908 BE 914	2ϕ6 1ϕ12 1ϕ14 1ϕ14 2ϕ16 2ϕ5	ϕ5 d: 22 cm
T202	60x18	BE 902 BE 906 BE 909 BE 913	2ϕ6 1ϕ12 1ϕ12 1ϕ12 2ϕ12 2ϕ5	ϕ5 d: 22 cm
T203	60x18	BE 903 BE 905 BE 910 BE 912	2ϕ5 2ϕ6 1ϕ14 1ϕ14 1ϕ14 1ϕ16 2ϕ5	ϕ5 d: 22 cm
T204	60x18	BE 920	2ϕ6 1ϕ16 1ϕ16 2ϕ16	ϕ5 d: 22 cm
T205	60x18	BE 919	2ϕ6 1ϕ16 1ϕ16 2ϕ16	ϕ5 d: 20 cm
T206	25x70	BE 918 BE 921	2ϕ6 1ϕ10 1ϕ10 2ϕ12	
T207	25x70	BE 904 BE 911	2ϕ6 1ϕ10 1ϕ10 2ϕ12	
T208	25x40	CB 901 CB 907 CB 908 CB 914	2ϕ6 1ϕ12 1ϕ12 1ϕ12 2ϕ12 1ϕ5	ϕ5 d: 20 cm
T209	25x40	CB 902 CB 906 CB 909 CB 913	2ϕ6 1ϕ10 1ϕ10 1ϕ10 2ϕ12 2ϕ5	
T210	25x40	CB 103 CB 104 CB 105 CB 910 CB 911 CB 912	2ϕ6 1ϕ10 1ϕ10 1ϕ10 2ϕ5	ϕ5 d: 20 cm
T211	55x18	BE 915 BE 916 BE 923 BE 924	2ϕ5 1ϕ16 1ϕ14 1ϕ14 2ϕ16	ϕ5 d: 20 cm
T212	55x18	BE 917 BE 922	2ϕ5 1ϕ16 1ϕ16 1ϕ16 2ϕ16	ϕ5 d: 20 cm

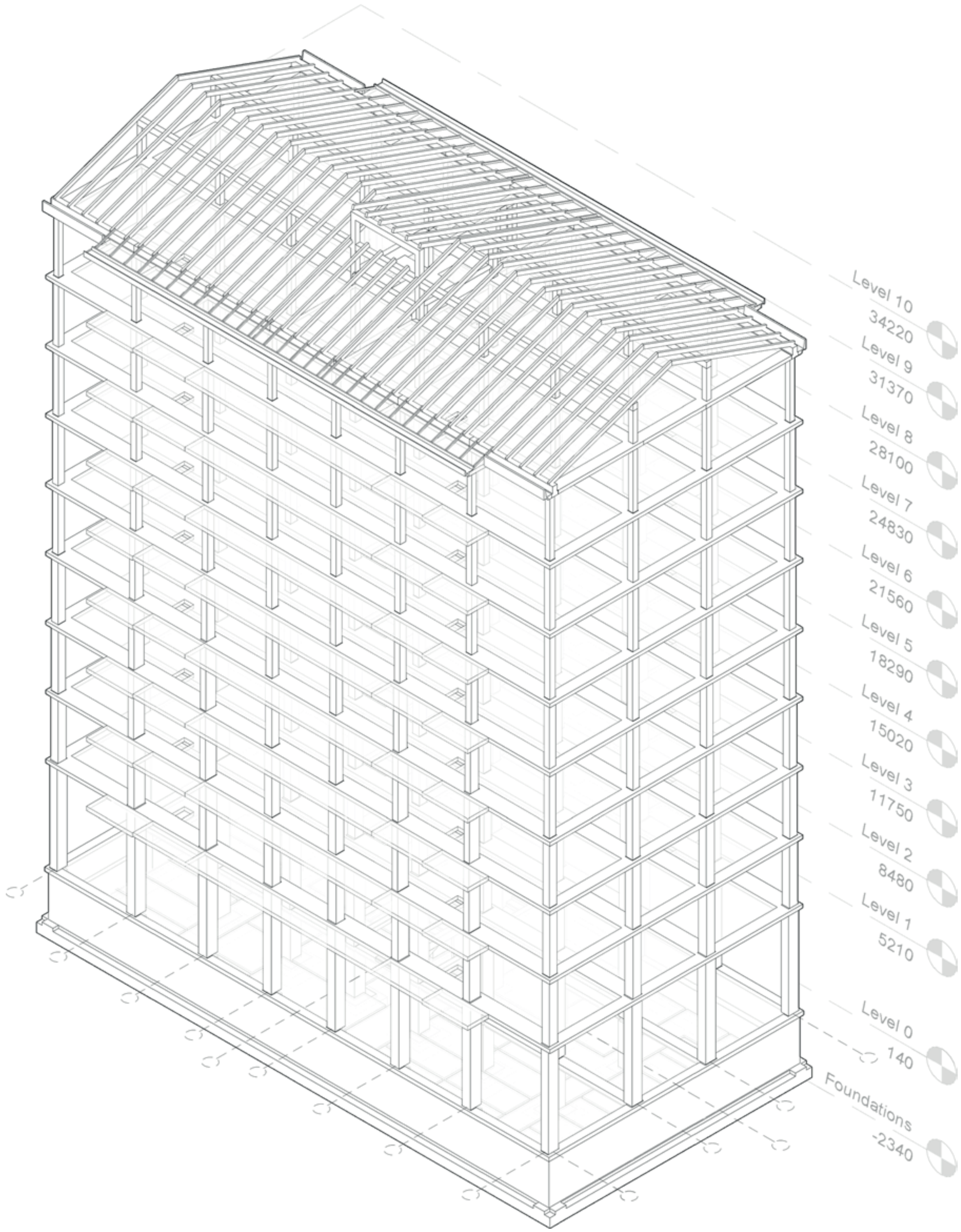
Structural details
MATERIALS PROPERTIES

Floors	Structural element	Material (Documented)	Properties (D.L. 2229/1939)		Material (Model)	Properties (Model)		CF_{KLn}
Foundations	Beams	-		-	-		-	
	Columns	-	R_{ck} [kg/cm²]	-	-	R_{ck} [MPa]	-	
	Slabs	-		-	-		-	-
	Walls	-		-	-		-	
	Reinforcing	-	f_{ck} [kg/mm²]	-	-	f_{ck} [MPa]	-	
Ground floor	Beams	Tipo 500		120	C12/15		12	1.35
	Columns	Tipo 500	R_{ck} [kg/cm²]	120	C12/15	R_{ck} [MPa]	12	
	Slabs	-		-	(diaphragm)		(infinite)	-
	Reinforcing	Ferro semiduro	f_{ck} [kg/mm²]	27	Fe225K	f_{ck} [MPa]	225	-
Typical floors	Beams	Tipo 680		160	C16/20		16	1.35
	Columns	Tipo 680	R_{ck} [kg/cm²]	160	C16/20	R_{ck} [MPa]	16	
	Slabs	-		-	(diaphragm)		-	-
	Reinforcing	Ferro semiduro	f_{ck} [kg/mm²]	27	Fe225K	f_{ck} [MPa]	225	-
Roof	Beams	Legno	-	-	-	-	-	-

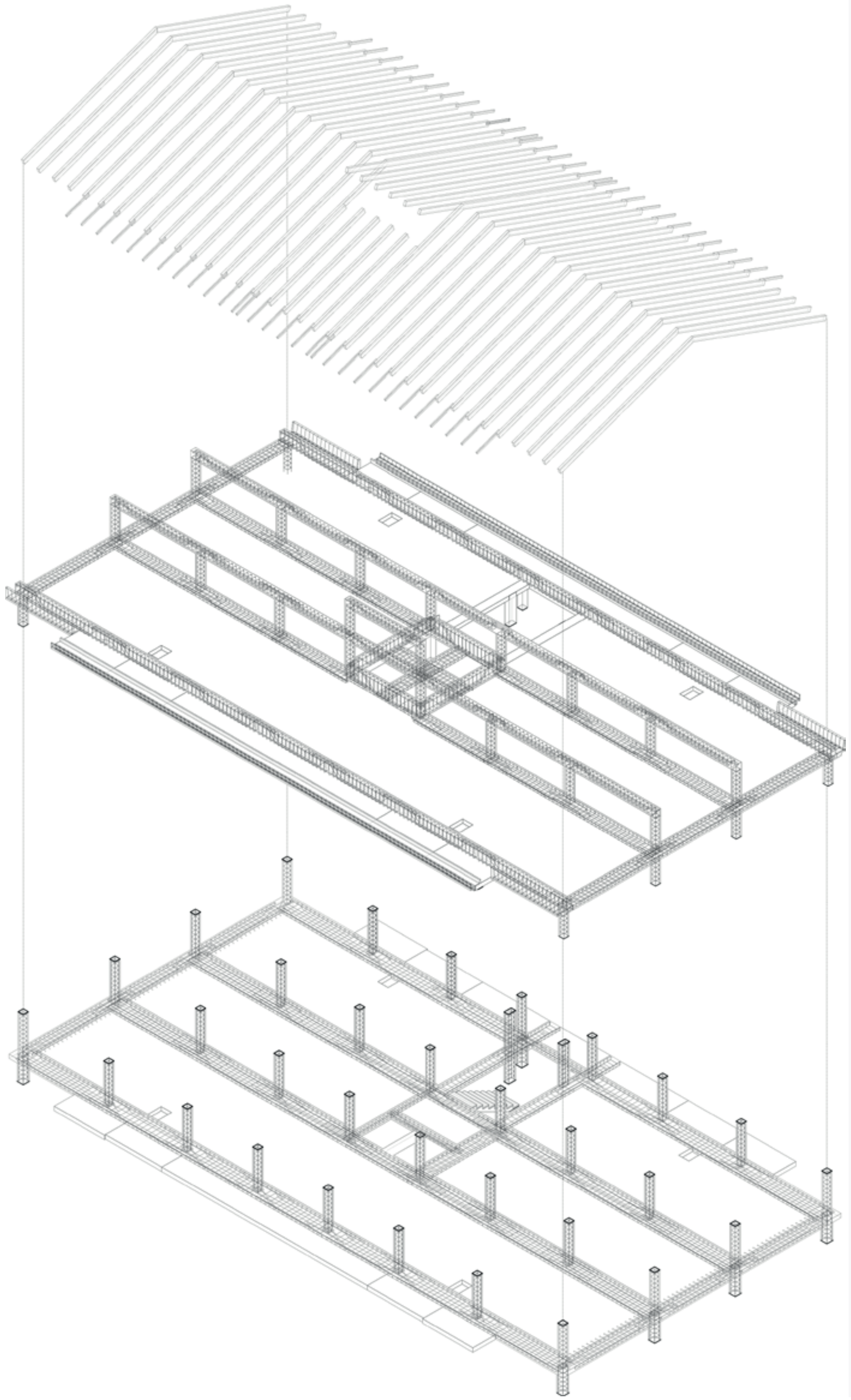
Structural modelling

The modelling process of the selected case study has been carried out with the use of the Autodesk Revit 2020 software. The BIM methodology allowed us to sort and represent efficiently the informations gathered from the original project's documentation. The modelling began with the definition of the general characteristics of the building's geometry (storeys' number, storeys' height, general dimensions in plan). These have been transferred to the BIM model using the standard tools provided by Revit: levels and structural grids. Subsequently, the precise definition of geometry and sections of the structural elements required the definition of several custom families and types of elements, in order to guarantee a digital model as true as possible to the original, in terms of definition and positioning of the original structural elements and of their basic material properties. The classification of structural elements in schedules have been carried out with an improved degree of automation thanks to custom Dynamo scripts, useful in particular to sort the informations of the large number of beams, columns and slabs according to their different properties. The definition of reinforcements have been carried out manually, and proofed to be one of the most time-demanding tasks in terms of modelling (and which, unfortunately, proved also useless in terms of integration with chosen the structural analysis software). However, the long and detailed initial modelling process proved, on the other, hand very useful due to the requirements in terms of interdisciplinarity. With regard to both the joint work on the structural design and analysis and the Life-Cycle Assessment process, the availability of at hand detailed data about geometries, quantities and weights allowed for a simpler, faster and more precise cooperation and communication of the gradual project and analysis' improvements.

Revit structural model
AXONOMETRIC VIEW



Revit structural model
EXPLODED AXONOMETRIC VIEW



ROOF
Bottom: + 31.37 m
Ridge: + 34.22 m
Slope: 36%

Structural framing:
Wood Beams, 100x200
Wood Beams, 50X80

Structural materials:
Wood: 29.17 m^3

9^{th} FLOOR (attic)
Level: + 31.37 m

Structural framing:
RC Cornice, 25x40
RC Beams, 25x40
RC Beams, 25x70
RC Beams, 55x18
RC Beams, 60x18
RC Beams, 25x30

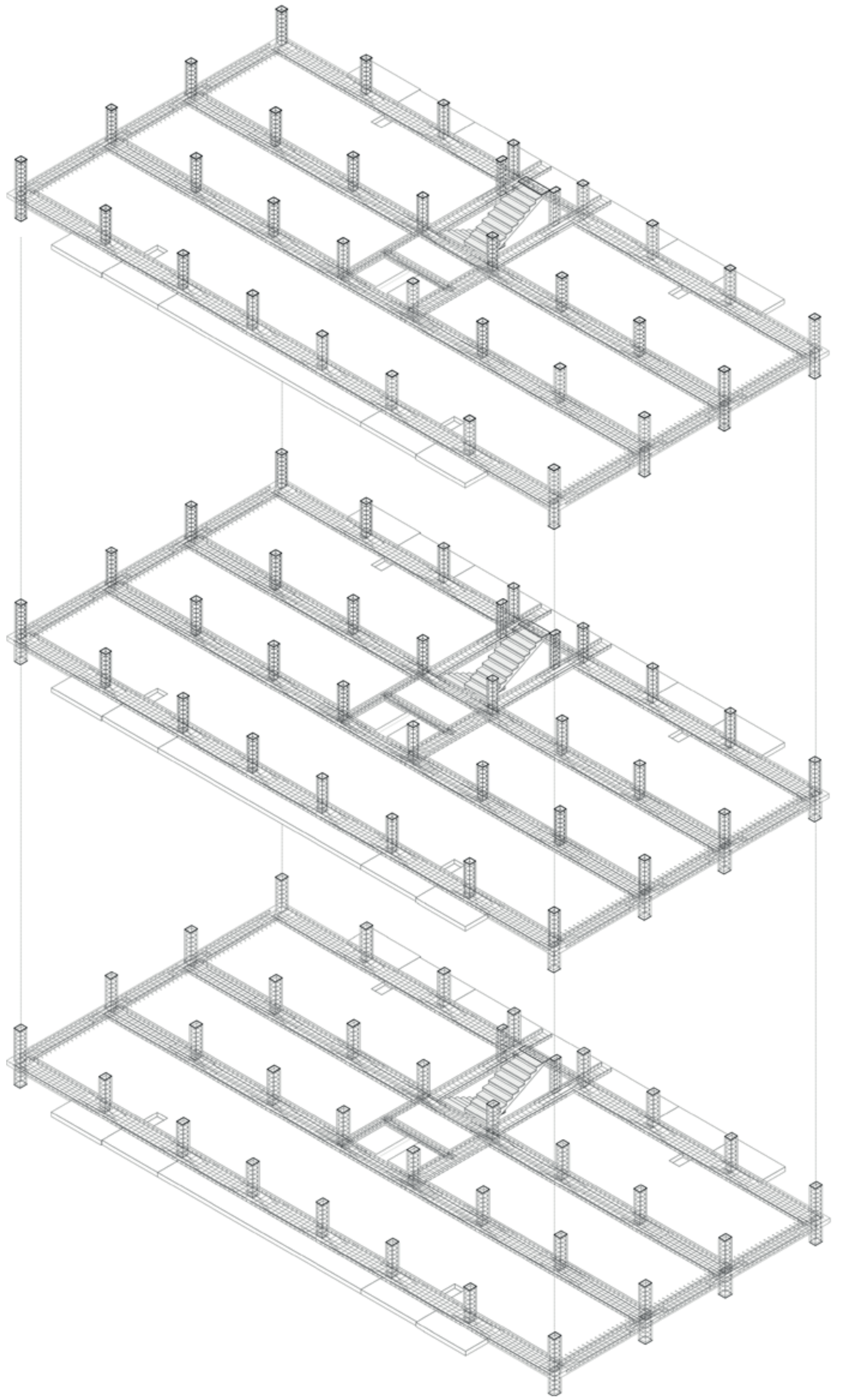
Structural materials:
Concrete: 25.44 m^3
Reinf. steel: 0.16 m^3

8^{th} FLOOR
Level: + 28.10 m

Structural framing:
RC Beams, 30x18
RC Beams, 35x18
RC Beams, 55x18
RC Beams, 60x18
RC Beams, 70x18
RC Beams, 72.5X25
RC Beams, 85X18

Structural materials:
Concrete: 19.48 m^3
Reinf. steel: 0.24 m^3

Revit structural model
EXPLODED AXONOMETRIC VIEW



7^{th} FLOOR
Level: + 24.83 m

Structural framing:
RC Beams, 30x18
RC Beams, 35x18
RC Beams, 55x18
RC Beams, 60x18
RC Beams, 70x18
RC Beams, 72.5X25
RC Beams, 85X18

Structural materials:
Concrete: 19.48 m^3
Reinf. steel: 0.24 m^3

6^{th} FLOOR (attic)
Level: + 21.56 m

Structural framing:
RC Cornice, 25x40
RC Beams, 25x40
RC Beams, 25x70
RC Beams, 55x18
RC Beams, 60x18
RC Beams, 25x30

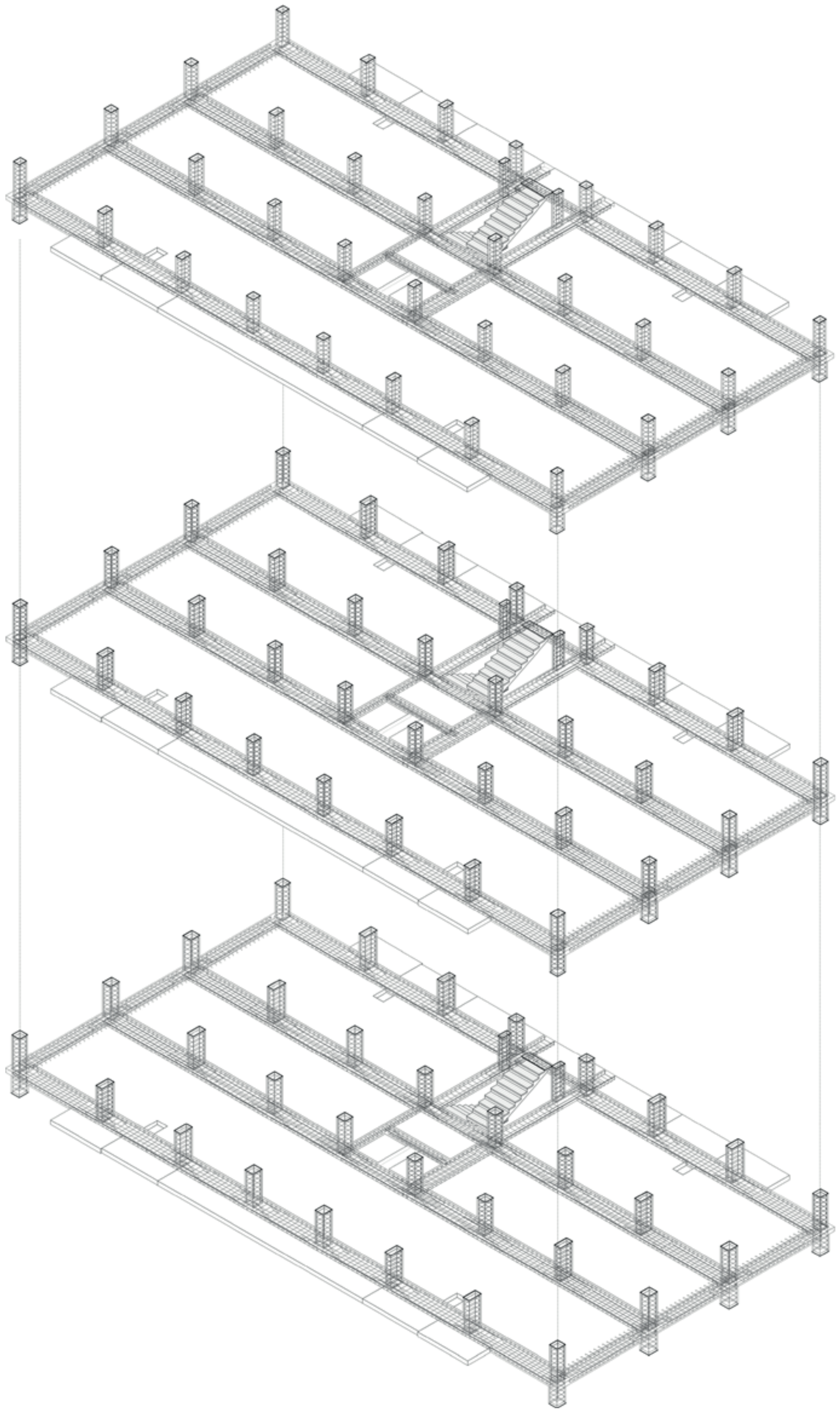
Structural materials:
Concrete: 22.39 m^3
Reinf. steel: 0.15 m^3

5^{th} FLOOR
Level: + 18.29 m

Structural framing:
RC Beams, 30x18
RC Beams, 35x18
RC Beams, 55x18
RC Beams, 60x18
RC Beams, 70x18
RC Beams, 72.5X25
RC Beams, 85X18

Structural materials:
Concrete: 19.48 m^3
Reinf. steel: 0.24 m^3

Revit structural model
EXPLODED AXONOMETRIC VIEW



4th FLOOR
Level: + 15.02 m

Structural framing:
RC Cornice, 25x40
RC Beams, 25x40
RC Beams, 25x70
RC Beams, 55x18
RC Beams, 60x18
RC Beams, 25x30

Structural materials:
Concrete: 22.39 m^3
Reinf. steel: 0.15 m^3

3rd FLOOR
Level: + 11.75 m

Structural framing:
RC Cornice, 25x40
RC Beams, 25x40
RC Beams, 25x70
RC Beams, 55x18
RC Beams, 60x18
RC Beams, 25x30

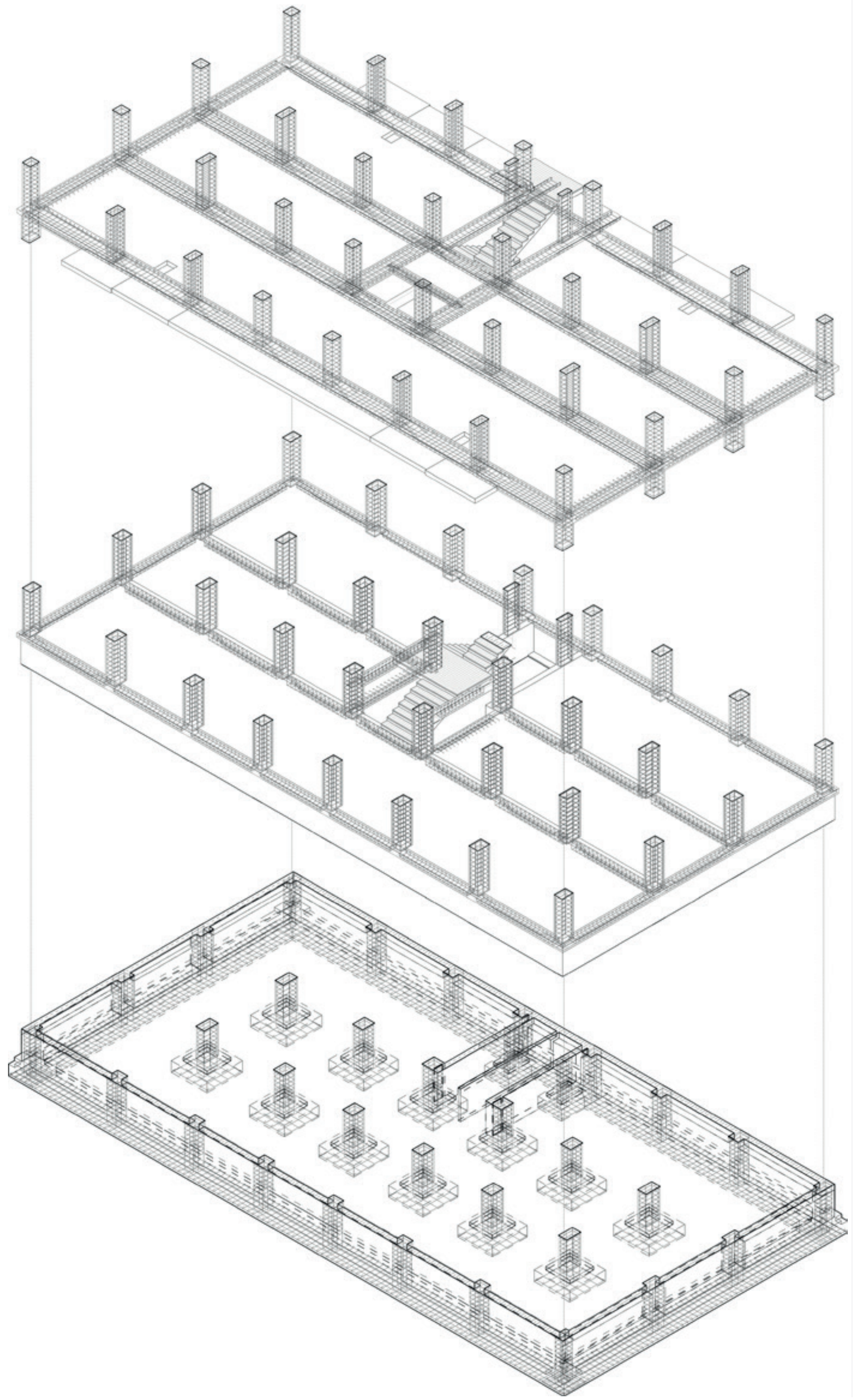
Structural materials:
Concrete: 22.39 m^3
Reinf. steel: 0.15 m^3

2nd FLOOR
Level: + 8.48 m

Structural framing:
RC Beams, 30x18
RC Beams, 35x18
RC Beams, 55x18
RC Beams, 60x18
RC Beams, 70x18
RC Beams, 72.5X25
RC Beams, 85X18

Structural materials:
Concrete: 19.48 m^3
Reinf. steel: 0.24 m^3

Revit structural model
EXPLODED AXONOMETRIC VIEW



1st FLOOR
Level: + 5.21 m

Structural framing:
RC Beams, 30x18
RC Beams, 35x18
RC Beams, 55x18
RC Beams, 60x18
RC Beams, 70x18
RC Beams, 72.5X25
RC Beams, 85X18

Structural materials:
Concrete: 19.48 m^3
Reinf. steel: 0.24 m^3

GROUND FLOOR
Level: + 0.14 m

Structural framing:
RC Cornice, 25x20
RC Beams, 30X35
RC Beams, 40X20
RC Beams, 25X35
RC Beams, 60x18
RC Beams, 25x30

Structural materials:
Concrete: 13.41 m^3
Reinf. steel: 0.10 m^3

FOUNDATIONS
Level: -2.34 m

Cont. foundations:
Foundation Beams

Isolated foundations:
RC Plints, 120x30
RC Plints, 115x30
RC Plints, 750x30

Structural materials:
Concrete: 77.82 m^3
Reinf. steel: 0.28 m^3

Analytical modelling

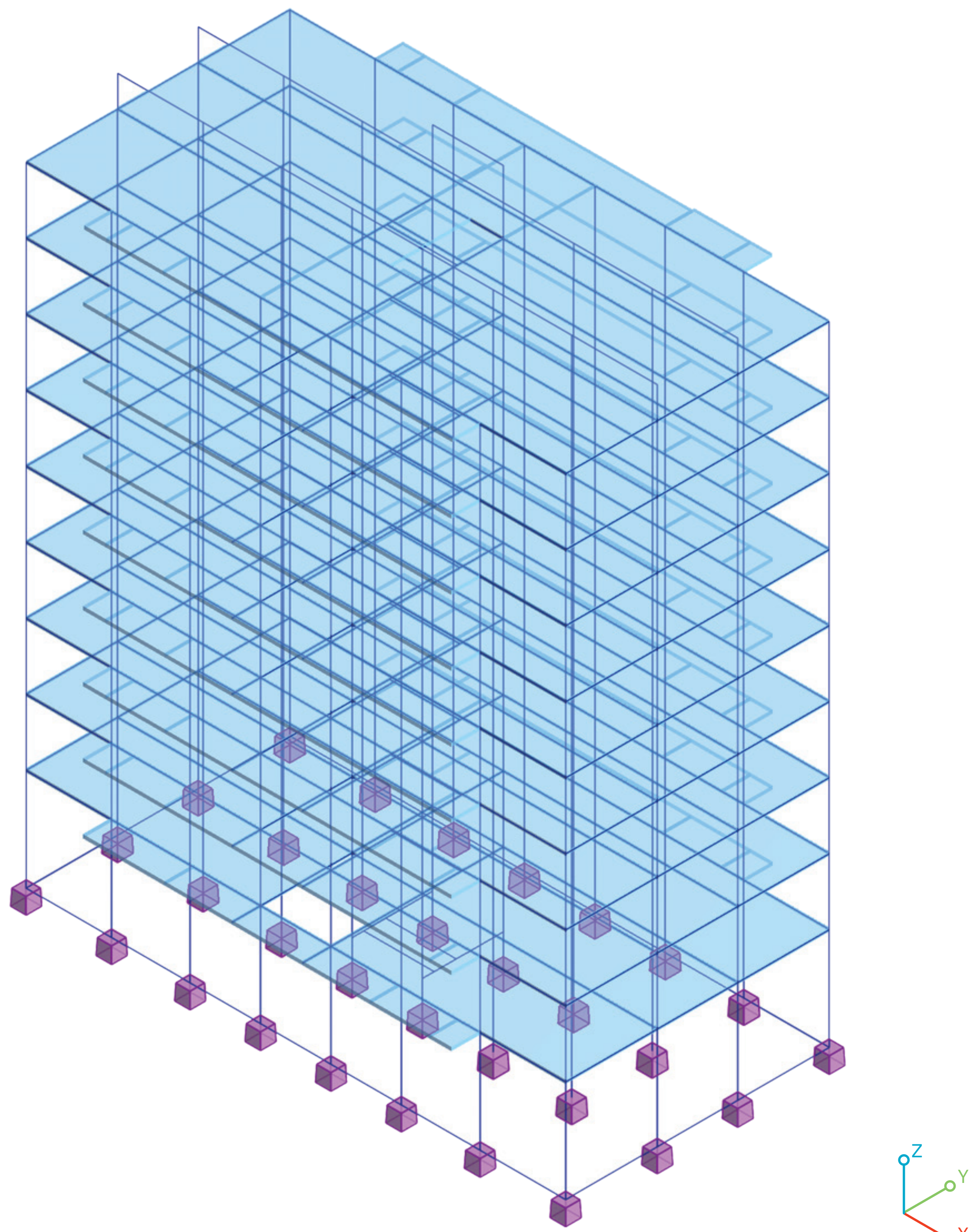
The choice of a calculation software for the seismic analysis of this case study has been a crucial and delicate stage of our process. In first place because, in order to optimise the adherence of the calculation model with the structural and architectural one created in Autodesk Revit 2020, it proved necessary to reach a high end interoperability between the applications, due to the large amount of data embodied in the BIM model. This phase proved difficult above our expectations: the complexity of this process lies both in the high degree of precision and coherency required in the modelling process and in the specific experience regarding the different structural analysis applications' features. Each trial consisted in subtle improvements to the previous attempt, leading often to unexpected or rather disappointing results. However, although being quite a time demanding task, this "cut and try", iterative process gave us the opportunity to experiment some different topics which, far from being the main concern of this thesis, are indeed a crucial aspect of the contemporary highly interdisciplinary design practices. For instance, the performance of the IFC (*Industry Foundation Class*) file format, industry standard for the communication between BIM applications, proved poor abilities in the management of structural data and properties of the analytical models, rather being limited (at present times) quite solely to the geometric properties of the 3D objects. With regard to the issue of knowledge, an improvement in this regard would constitute a much desirable feature, in order to facilitate such methodological approaches to the retrofit of existing constructions.

Finally, our choice fell back on the Autodesk Robot 2020 software: for, if the renowned steep learning curve of this application caused not a few issues and doubts at the beginning, the much easier import process of models from Revit empowered us with enhanced abilities to experiment different structural configurations in the early design stage with relative ease. However, it was never possible to achieve a complete and flewless integration. In particular, it proved necessary to repeat the modelling of some elements within the anlysis software:

- Structural foundations (constrains) and member releases
- Material properties
- Reinforcements (beams and columns)
- Various (often unexpected) other Revit's analytical model inconsistencies

In conclusion, we considered how crucial the topic of interoperability is to the application of this methodological approach: once the action of transferring informations between the two software was perfected, our efforts could head solely on the specific issues of the structural and seismic analysis and design challenge. The achievement of this ability is requires high experiences and competencies in structural modelling, in order to adopt the proper simplifications and shortcuts within the process.

Robot analytical model
AXONOMETRIC VIEW



Structural analysis

Once the structural model is imported and the absence of errors is checked, we proceed with the definition of loads and load combinations. These are defined according to the actual design code specifications, in order to verify the performance of the existing constructions with regard to the actual requirements of the design code.[01] Loads considered are divided in:

DL1: self weight of the structural components

PERM2: permanent loads due to the self weight of non-structural elements

UTIL1: variable free actions (or imposed loads), depending on the usage

Autodesk Robot 2020 is a FEM (*Finite Element Modelling*) software. It allows to perform any kind of seismic analysis: linear and non-linear, static or dynamic simulations. A key step when approaching any structural analysis lies in the definition of the objectives of the analysis itself. Our scope is to analyse the degree of seismic safety of the existing construction and, subsequently, to design a seismic retrofit intervention by means of an external exoskeleton structure, testing out a set of different structural solutions, ultimately defining the preliminary dimensions of the chosen retrofit scheme. Main parameters to be checked are the inter-storey drifts and overall displacements of the structure pre- and post-intervention, whilst monitoring the effect of the exoskeleton structure on base shear forces, accelerations and centre of gravity and rigidity of the case study. Given these premises and the available degree of information about the building, we decided to pursue these objectives by performing a dynamic linear (modal) analysis for both the existing and retrofitted models.

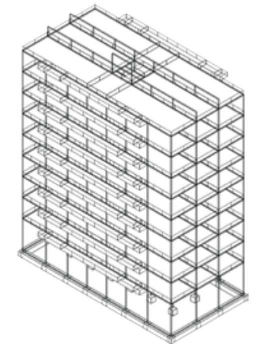
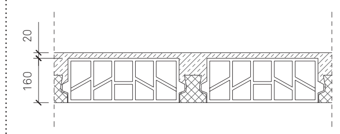
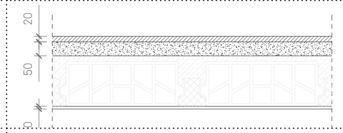
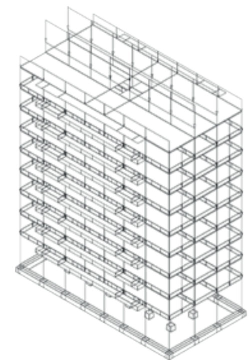
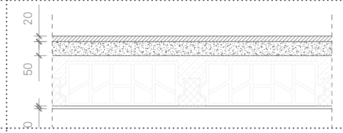
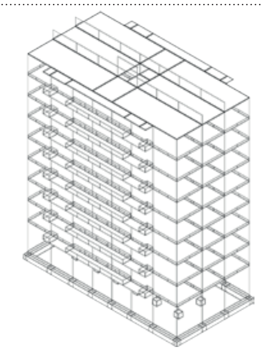
In order to run the modal analysis, it is in first place necessary to set the directions of vibration (for the sake of this experimentation, only the planar X and Y directions have been taken into account) and the number of modes to be considered (worth to reach a rate of excited mass higher than 85% in both directions). The damping coefficient of the structure is set to a default value of 0.05, hence considering negligible a more detailed evaluation of the damping capacity. The above mentioned loads are then converted into modal masses, considering the full amount for permanent loads (structural and non structural ones) and a reduction of 30% for live loads.

Afterwards, the parameters of limit states and seismic analysis are defined according to the specifications given by the national design codes. Autodesk Robot 2020, unfortunately, integrates only the obsolete version of the Italian structural code.[02] The prescriptions of this code's version, however, do not differ consistently in the recent update: the usage period and service class definition is the same, and so it goes for the description of soil categories and of topography. A notable amendment took place, however, in the definition of the *q-factor*, used to define the behaviour of the structure: low-dissipative structures do not imply any hysteretic energy dissipation, while dissipative structures are able to develop plastic overstrengths in some critical regions.

[01] D.M. 17 gennaio 2018, in materia di "*Aggiornamento delle «Norme tecniche per le costruzioni»*"

[02] D.M. 14 gennaio 2008, in materia di "*Approvazione delle «Norme tecniche per le costruzioni»*"

Robot analytical model
LOAD CASES

Load case	Element	Value		Detail / Description	Allocation
DL1	RC Frame (Beams, Columns)	25 kN/m³	1	Self weight of structural frame's elements (beams and columns)	
	RC Slabs	1.02 kN/m² + 1.30 kN/m² = 2.32 kN/m²	1		
PERM2	Interiors	1.15 kN/m²	1		
	Balconies	1.15 kN/m²	1		
	Facade	5.90 kN/m	1	Average linear load of perimetral walls	
	Roof (2/3)	3.33 kN/m	1	Average linear load of roof's components	
	Roof (1/3)	6.67 kN/m	1		
	Partition walls	1.20 kN/m²	1	Average distributed loads of partition walls	
UTIL1	Residential	2.00 kN/m²	1	Live loads (according to NTC 2018)	
	Balconies Stairwell Common spaces	4.00 kN/m²	1	Live loads (according to NTC 2018)	
	Maintenance (Roof)	0.50 kN/m²	1	Live loads (according to NTC 2018)	

The *q-factor* is a reduction parameter of the seismic acceleration spectra applied to the building. The relationship that binds them is:

[1] $S_d(T) = S_e(T)/q$

Where:

$S_d(T)$: ordinates of the design accelerations spectrum

$S_e(T)$: ordinates of the elastic accelerations spectrum

Load combinations are generated automatically: the structural response is assessed at all four limit states. The seismic accelerations are provided within the software settings, prior definition of the coordinates of the

Structural analysis
KEY INPUT PARAMETERS

Modal Analysis	Load case	Direction	Coefficient [-]	Directions
Loads to mass conversion	DL1	-Z	1	X, Y, Z
	PERM2	-Z	1	X, Y, Z
	UTIL1	-Z	0.7	X, Y, Z

Seismic input parameters (NTC 2018)	Value	Parameter	Value	Description
Usage period	-	V_N [years]	50	Ordinary performance degree constructions
Service class	II	C_U [-]	1	Buildings whose use implies normal crowding, without dangerous contents for the environment and without essential public and social functions
Localisation	-	Coordinates	-	Longitude: 45.0781 Latitude: 7.6761
Soil category	C	-	-	Dense sand or gravel or stiff clay
Topography	T1	-		Flat surface, isolated slopes and reliefs with average inclination I < 15°
Limit states	SLS	q-factor (non dissipative)	1	A unitary q-factor has been chosen for each limit state: no hysteretic energy dissipation is accounted at any degree of acceleration.
	DLS		[1; 1.5]	
	LLS		[1; 1.5]	
	CLS		-	
Direction definition	X	[-]	1	None of the resulting load combinations will consider vertical loads in direction Z
	Y	[-]	1	
	Z	[-]	0	

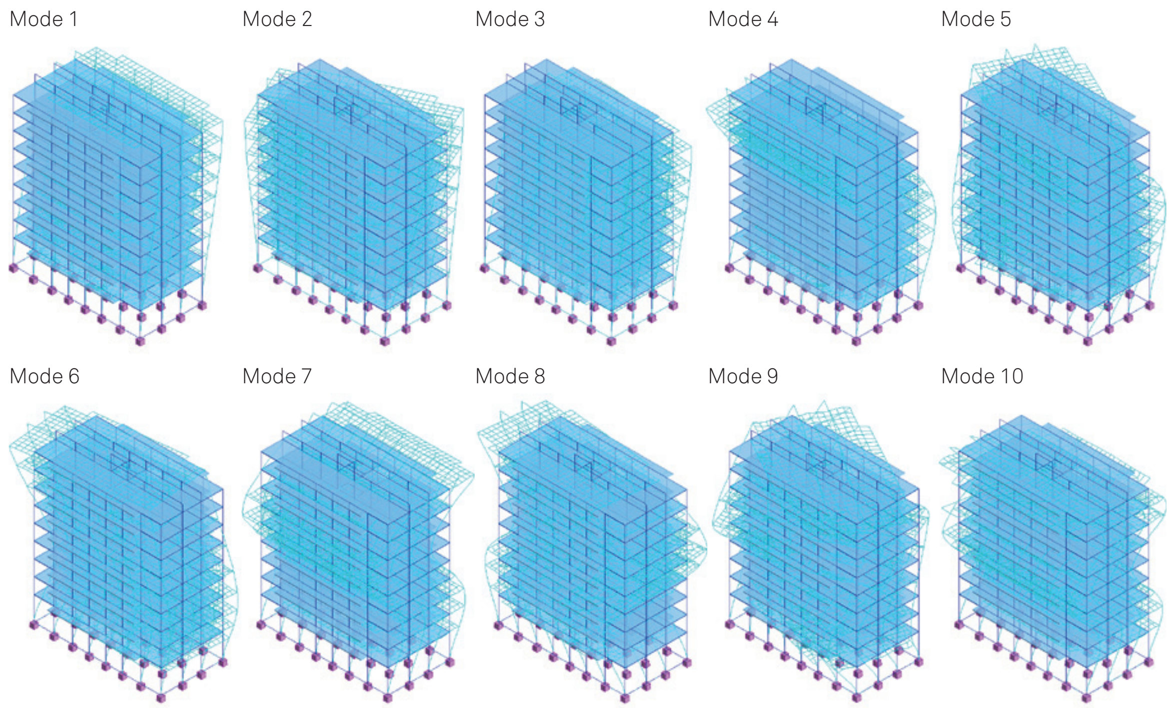
Loads combinations	Limit state	Definition	Analysis type
SLS	SLS	X + 0.3Y	Linear Combination
	SLS	X - 0.3Y	Linear Combination
	SLS	0.3X + Y	Linear Combination
	SLS	0.3X - Y	Linear Combination
	DLS	X + 0.3Y	Linear Combination
	DLS	X - 0.3Y	Linear Combination
	DLS	0.3X + Y	Linear Combination
	DLS	0.3X - Y	Linear Combination
ULS	LLS	X + 0.3Y	Linear Combination
	LLS	X - 0.3Y	Linear Combination
	LLS	0.3X + Y	Linear Combination
	LLS	0.3X - Y	Linear Combination
	CLS	X + 0.3Y	Linear Combination
	CLS	X - 0.3Y	Linear Combination
	CLS	0.3X + Y	Linear Combination
	CLS	0.3X - Y	Linear Combination

building. We chose to evaluate the structure according to two kinds of combinations: ultimate and serviceability limit states combinations, each considering different arrangements on both axial directions (X , Y). The global extremes of displacements and inter-storey drifts, among all the combinations created, are used as the main design parameter for the simulation of the exoskeleton structure as well. At the *damage limit state*:

Structural analysis
MODAL ANALYSIS RESULTS

Mode	f [Hz]	T [s]	Mass participation ratio [%]			Total mass [t]	Effective participation ratio and mass [%] [t]					
			X	Y	Z		X		Y		Z	
1	0.52	1.91	0.00	78.67	0.00	3094.71	0.00	-	78.67	2434.61	-	-
2	0.55	1.81	0.83	78.67	0.00		0.83	25.67	0.00	-	-	-
3	0.56	1.79	80.05	78.67	0.00		79.22	2451.63	0.00	-	-	-
4	1.48	0.68	80.06	90.19	0.00		0.00	-	11.52	356.51	-	-
5	1.55	0.65	80.59	90.19	0.00		0.54	16.71	0.00	-	-	-
6	1.56	0.64	91.72	90.19	0.00		11.13	344.44	0.00	-	-	-
7	2.55	0.39	91.72	94.23	0.00		0.00	-	4.04	125.03	-	-
8	2.63	0.38	95.32	94.23	0.00		3.60	111.41	0.00	-	-	-
9	2.66	0.38	95.45	94.23	0.00		0.13	4.02	0.00	-	-	-
10	3.56	0.28	95.45	96.28	0.00		0.00	-	2.54	78.60	-	-
						Totals of the relevant modes:	90.35	2796.07	90.19	2791.12	-	-

Structural analysis
MODES OF VIBRATION

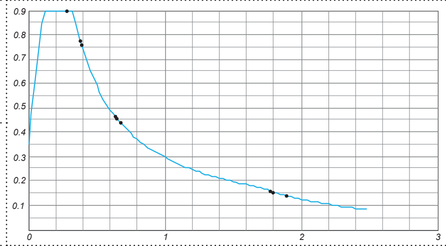
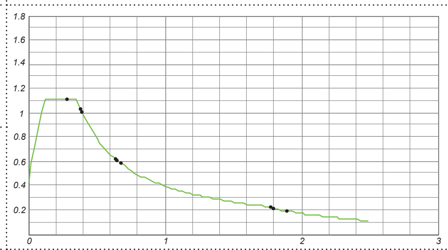
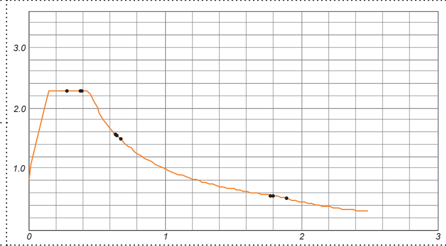


[2] $qd_r \leq 0.0050 \cdot h$

Where:
qd_r: inter-storey drifts
h: inter-storey height

Finally, we decided to take into consideration the comparison between the response spectra, accelerations and consequent base shear forces.

Structural analysis
RESULTS

Limit State		T_R [years]	a_g [g]	F_0 [-]	T_C^* [s]	Acceleration spectra
SLS	X	30	0.236	2.579	0.177	
	Y	30	0.236	2.579	0.177	
DLS	X	50	0.292	2.588	0.196	
	Y	50	0.292	2.588	0.196	
LSL	X	475	0.560	2.759	0.272	
	Y	475	0.560	2.759	0.272	
CLS	X	975	0.664	2.807	0.287	
	Y	975	0.664	2.807	0.287	

Limit State	$s_{X,max}$ [mm]	$s_{Y,max}$ [mm]	$V_{X,max}$ [kN]	$V_{Y,max}$ [kN]	Story drifts [mm] (Above: X, Below: Y)								
					1st	2nd	3rd	4th	5th	6th	7th	8th	9th
SLS	17	18	434.11	388.89	2	5	7	9	12	14	15	16	17
					2	5	7	9	11	13	15	17	18
DLS	23	25	580.90	519.20	3	6	10	13	15	18	21	22	23
					3	6	9	12	15	18	21	22	25
LSL	62	66	1522.39	1372.17	9	17	25	33	41	48	54	59	62
					8	16	25	33	41	49	56	61	66
CSL	78	85	1902.62	1744.12	11	21	34	42	51	60	68	74	78
					10	20	32	43	53	62	71	78	85

Exoskeleton: modelling and analysis

The exoskeleton modelling process followed the same metodology used for the existing building. Within the same Revit model we modelled, in the early design stage, a few different structural configurations, which were subsequently improved and discussed in the following weeks, with regard to the structural, architectural and construction implications of each. The chosen typology, hence, is the result of a process of trial and error of different prototypes, in order to reach a configuration that would satisfy most of our requirements. The main issues, collectively discussed, were:

Structural optimisation, regarding the specific qualities and issues of the existing building

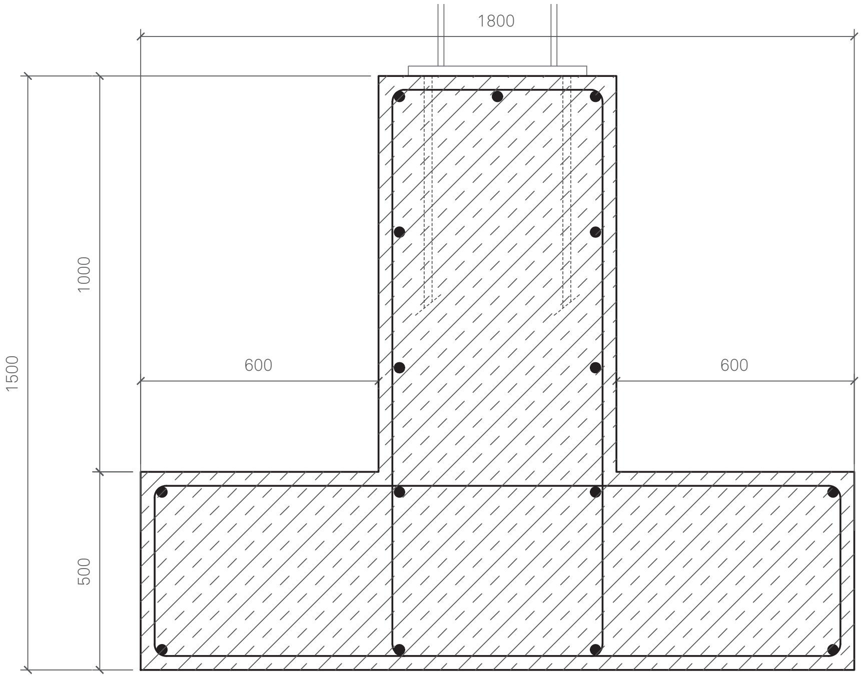
Architectural quality and possibilities: flexibility/adaptivity of the scheme

Demolitions and structural material usage

Constructability and feasibility

Also with regard to this stage, the BIM methodology and the Autodesk Revit 2020 were integral part of this process. The usage of design options and project phases (tools of this software) allowed for an easy modelling and communication tool for the different design proposals. In particular, the fast modelling process allowed for a structural prototyping process in which, prior some more demanding tasks as the beginning (the definition of schedules and consolidation of the analytical models), it had been possible to test several solutions at once, while constantly monitoring the usage of materials (for the parallel LCA study) and the structural performance. In this respect, the excellent degree of interoperability among the Autodesk software Revit 2020 and Robot 2020 allows to update the exoskeleton structure on the already consolidated analytical model of the existing building. The importance of this aspect is far from underestimating, rather it opens up to a much desirable methodology while approaching retrofit projects of existing constructions: the rapid prototyping of solution and their optimisation, without prejudice of the previous considerations made thanks to the accurate modelling process of the existing building.

The exoskeleton's analytical modelling, however, presented some peculiar challenges. Two topics, in particular, were addressed with particular care: the design of the new frame's foundations and the connection of the new external structure to the existing one. For the sake of our analysis, the new foundations had to be designed within the structural analysis model, in order to obtain a correct definition of materials and sections, and of the structural behaviour of the foundation. The choice fell, since the beginning, on continuous foundations, outdistanced from the original ones: Autodesk Robot 2020 allows the modelling of continuous foundation beams and the customisation of section shapes, materials and of the soil's behaviour model. In this respect, we chose the *Winkler model*, which compares the soil to a number of adjoined discrete,independent, linear elastic springs. The



FOUNDATION BEAMS

Section: T shape

180x50/60x100

A_x: 15000.00 cm^2
I_x: 10571366.60 cm^4
I_y: 27125000.00 cm^4
I_z: 26100000.00 cm^4

Structural material:

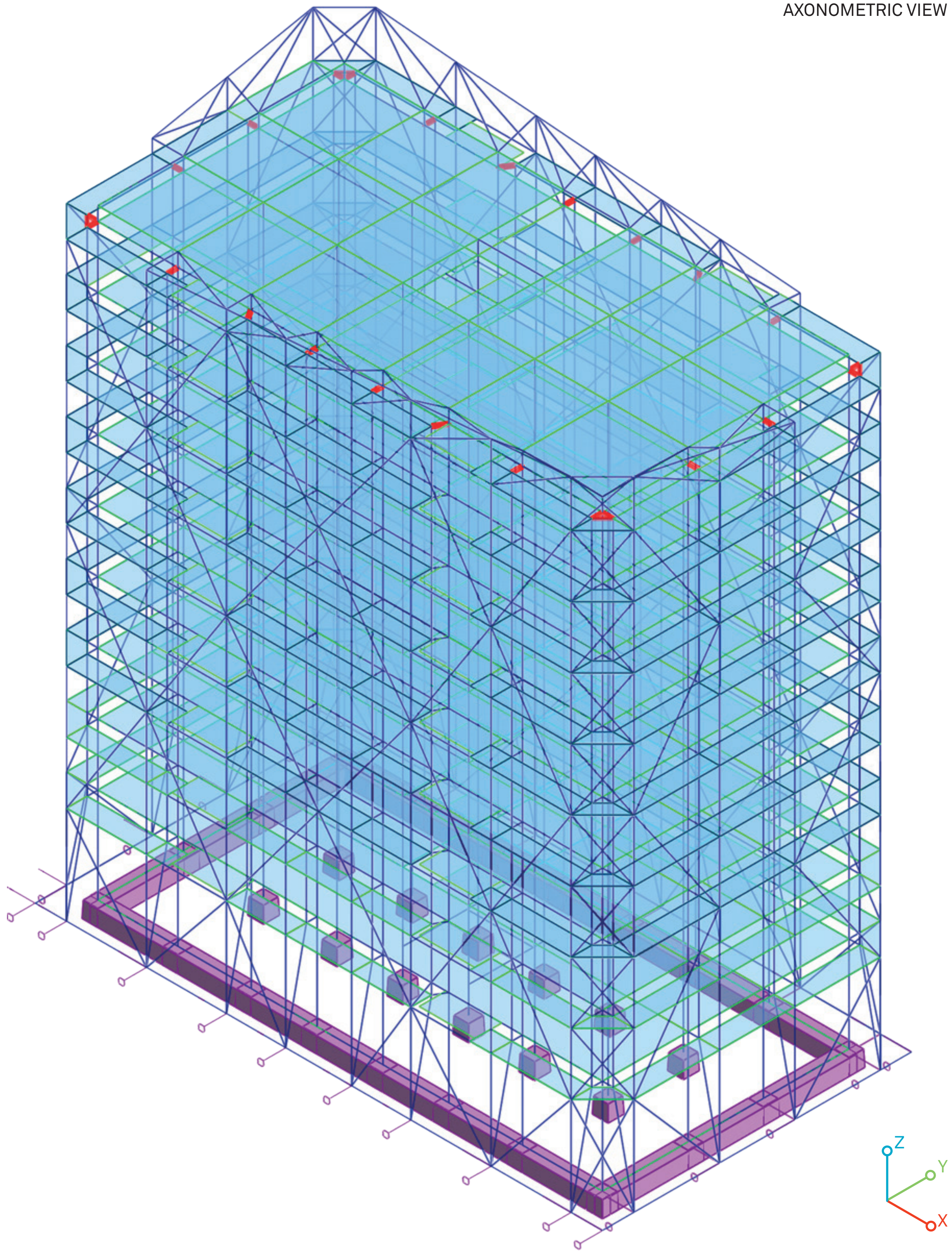
Concrete C28/35

W: 25 kN/m^3

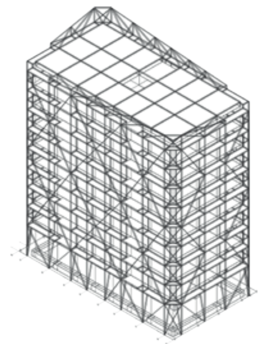
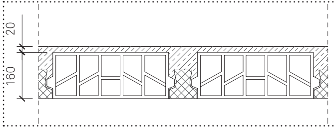
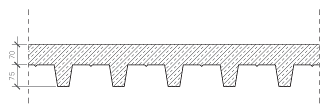
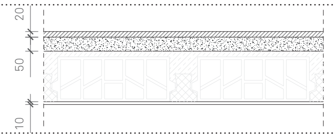
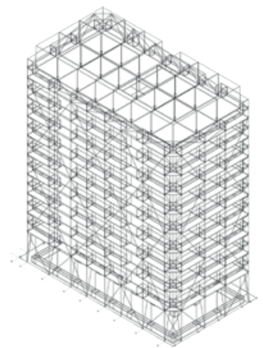
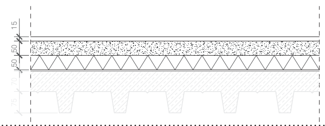
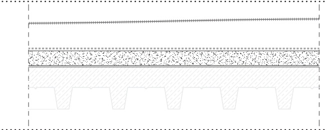
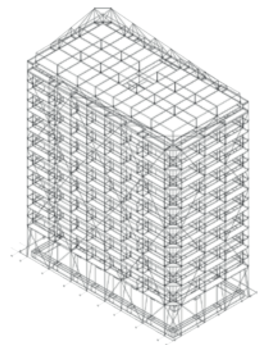
E: 28500.00 MPa
G: 16300.00 Mpa
NI: 0.17

main design parameter is the definition of the stiffness of the springs, and indeed of the geometrical and material properties of the foundation beams. The issue of the exoskeleton's connection to the original structure has been solved employing another specific tool provided by the application, the *rigid link*. A rigid link is a virtual element of connection, able to block displacements and rotations in the directions of choice: the rigid links applied to our calculation model block all 6 degrees of freedom, providing an infinitely rigid connection between the original building and the external steel frame, as anticipated in the theoretical dissertation of the problem.

The process of analysis follows instead the exact same methodology: first, analysis parameters are set, than, prior definition of the load combinations, the calculations are launched. The self weight of the exoskeleton's steel is augmented by a 15%, in order to take into account, also in the preliminary stage of analysis, the weight of connections and of coating, and the boundary conditions (foundations of the exoskeleton and foundations of the original building) are moved at the ground level: the presence of an underground storey of the original building is neglected, since its behaviour is considered contiguous to that of the soil. The calculation is ran with regard to all four seismic limit states, and with full ultimate and serviceability load combinations (with regard to X and Y directions). Same goes for the definition of the unitary *q-factor* (non-dissipative behaviour, full elastic acceleration spectra) and for the key results parameters: interstory displacements at DLS, base shear forces and accelerations.



Exoskeleton: analytical model
LOAD CASES

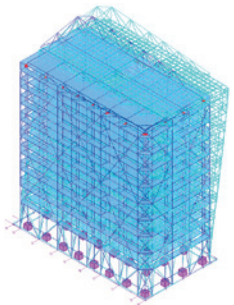
Load case	Element	Value		Detail / Description	Allocation
DL1	RC Frame (Beams, Columns)	25.0 kN/m³	1	Self weight of structural frame's elements (beams and columns)	
	Exoskeleton	78.5 kN/m³	1.15	Self weight of structural steel braces (augmented by 15% to include the coating)	
	RC Slabs	1.02 kN/m² + 1.30 kN/m² = 2.32 kN/m²	1		
	Steel-Concrete Slabs	2.30 kN/m² + 0.1 kN/m² = 2.40 kN/m²	1		
PERM2	Interiors	1.15 kN/m²	1		
	Balconies	1.25 kN/m²	1		
	Green roof	3.25 kN/m²	1		
	Facade	5.90 kN/m	1	Average linear load of perimetral walls	
	Partition walls	1.20 kN/m²	1	Average distributed loads of partition walls	
UTIL1	Residential	2.00 kN/m²	1	Live loads (according to NTC 2018)	
	Balconies Stairwell Common spaces	4.00 kN/m²	1	Live loads (according to NTC 2018)	
	Maintenance (Roof)	0.50 kN/m²	1	Live loads (according to NTC 2018)	

Starting out from the first calculations, it has been necessary to iterate the analysis many times in order to optimise the elements' size and configuration. We began with some assumptions about the sections to utilise (HE for columns, IP sections for beams and main structural braces, circular hollow sections for other braces, such as those in the corners). The results shown here relates to the final dimensions of the profiles: the process of analysis, however, began with wider profiles, such as HEA 300 and IPE 300 for columns and braces, IPE 240 for girders.

Exoskeleton: structural analysis
MODAL ANALYSIS RESULTS

Mode	f [Hz]	T [s]	Mass participation ratio [%]			Total mass [t]	Effective participation ratio and mass [%] [t]					
			X	Y	Z		X		Y		Z	
1	0.70	1.42	0.00	79.97	0.00	3856.99	0.00	-	79.97	3084.43	-	-
2	1.04	0.96	83.33	79.97	0.00		83.33	3214.03	0.00	-	-	-
3	1.46	0.68	83.34	79.97	0.00		0.01	0.38	0.00	-	-	-
4	2.55	0.39	83.34	92.43	0.00		0.00	-	12.45	480.20	-	-
5	3.26	0.31	93.59	92.43	0.00		10.25	395.34	0.00	-	-	-
6	4.46	0.22	93.59	92.43	0.00		0.00	-	0.00	-	-	-
7	4.55	0.22	93.59	96.26	0.00		0.00	-	3.84	148.11	-	-
8	5.21	0.19	96.84	96.26	0.00		3.25	125.35	0.00	-	-	-
9	6.11	0.16	96.84	97.37	0.00		0.00	-	1.11	42.81	-	-
10	6.83	0.15	98.08	97.37	0.00		1.24	47.83	0.00	-	-	-
						Totals of the relevant modes:	93.58	3636.37	92.42	3564.63	-	-

Exoskeleton: structural analysis
MODES OF VIBRATION

Mode 1

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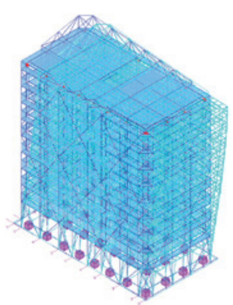
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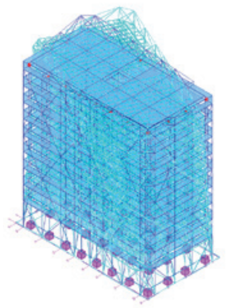
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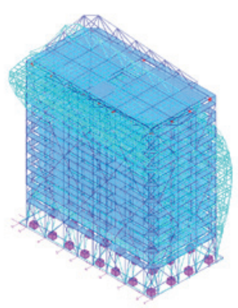
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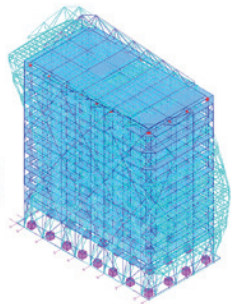
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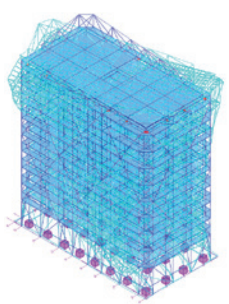
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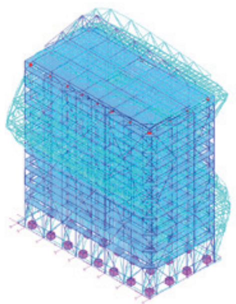
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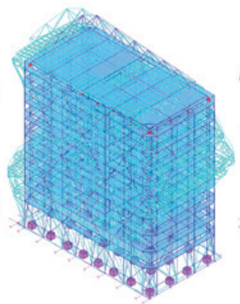
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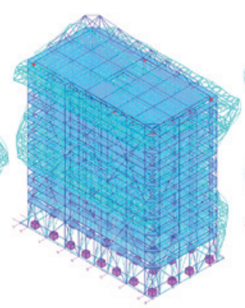
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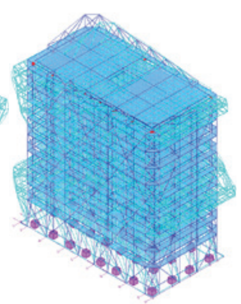
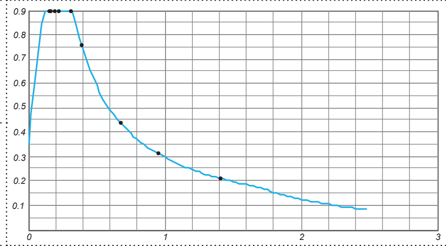
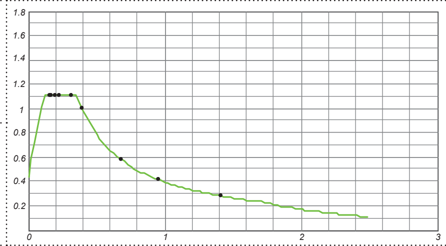
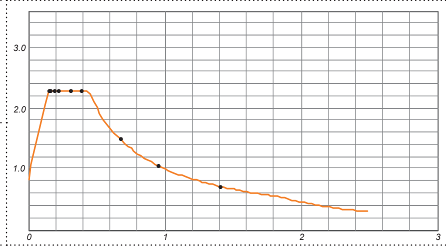


Conclusions

The final configuration uses HEA 240 profiles for the columns tapering to HEA 200 on top of the building, except for the columns on the short axes (HEA 300), which grant greater stiffness to the K braces configuration. IPE 240 profiles have been used for girders and braces on the long side, while IPE 200 were employed as braces in the upper storeys. Again, in order to confer

Structural analysis
RESULTS

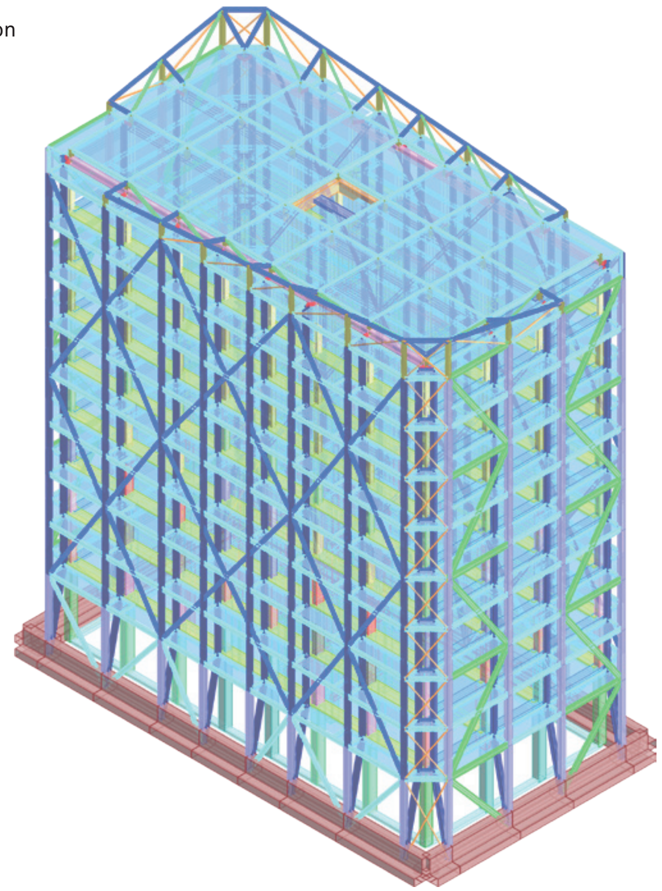
Limit State		T_R [years]	a_g [g]	F_0 [-]	T_C^* [s]	Acceleration spectra
SLS	X	30	0.236	2.579	0.177	
	Y	30	0.236	2.579	0.177	
DLS	X	50	0.292	2.588	0.196	
	Y	50	0.292	2.588	0.196	
LSL	X	475	0.560	2.759	0.272	
	Y	475	0.560	2.759	0.272	
CLS	X	975	0.664	2.807	0.287	
	Y	975	0.664	2.807	0.287	

Limit State	$s_{X,max}$ [mm]	$s_{Y,max}$ [mm]	$V_{X,max}$ [kN]	$V_{Y,max}$ [kN]	Story drifts [mm] (Above: X, Below: Y)								
					1st	2nd	3rd	4th	5th	6th	7th	8th	9th
SLS	10	15	1059.40	754.20	2	3	4	6	7	8	8	9	10
					2	4	6	7	9	10	12	13	15
DLS	13	19	1387.66	996.34	2	4	6	7	9	10	11	12	13
					2	5	7	10	12	14	16	18	19
LSL	32	49	3469.97	2461.84	5	10	14	19	22	26	28	31	32
					7	13	19	25	30	35	40	45	49
CSL	40	62	4329.30	3056.08	7	12	18	23	28	32	35	38	40
					8	16	23	31	38	44	51	57	62

Exoskeleton: final solution
STEEL SECTIONS

LEGEND:

- HEA 200
- HEA 240
- HEA 300
- IPE 200
- IPE 240
- IPE 300
- L 150X150X12
- Circular hollow 101x10



additional strength to the short side, the choice fell on IPE 300 for braces and for girders every two storeys (starting from the first), the latter being considered as posts of the vertical K braces configuration. The additional circular hollow and L profiles have been used, respectively, as braces for the corner solution and for the roof structure.

The results obtained with this configuration appear to us satisfactory. Displacements have been consistently reduced on both sides: it means that the overall stiffness of the construction has been enhanced. Another interesting aspect is the different layout of the modes of vibration: in the existing building, the frequency to which the structure engages a torsional stiffness is relatively low, becoming in fact the second mode. This underlines a lack of torsional stiffness, which eventually resolved in the analysis of the exoskeleton frame. As the stiffness grows, however, natural frequencies of vibration are generally higher: the modes with the exoskeleton configuration move towards higher values on the acceleration spectra, resulting in higher accelerations and base shear forces (due also to an increase of loads). This phenomenon was however expected: as the theoretical premises on the exoskeleton testify, the distribution of these forces is gathered for the most by the exoskeleton, hence protecting the original structure.

Existing construction's data

Contrarily to the adequate amount of details contained in the structural documentation, the architectural drawings lack of in depth physical data of about the envelope components. These drawings, however, allowed us to reconstruct the different typologies and their geometric configurations in plan and elevation.

Also in respect to the architectural and technical drawings, it was necessary to organise the documentation in:

- Architectural plans
- Architectural sections
- Detailed sections
- Windows details

These documents were, in most cases, sufficient to model the dimension and layering of the envelope components. When such informations were missing, assumptions have been made according to the technological solutions typical at the time of design and construction of the case study.

Unfortunately, the documentation at our disposal did not contain any detailed informations about the thermal and physical properties of these components: this issue is common to most of the building heritage that was built before of the introduction of the first requirements in terms of energy efficiency. Very low consideration, in fact, was given to the ability of the envelope to control the thermal and vapour transfers between outside and inside. Given this common issue, the Italian technical norms provide the values to be used in the evaluation of the energy performance of existing building envelopes. The first stage implied, in fact, the confrontation of the typologies of this case study with the different databases provided by technical norms. Subsequently, in case of missing informations, data have been gathered from research projects, such as *TABULA* (Typical Approach for Building Stock Energy Assessment, which encompass a large number of building typologies, organised according to their construction years). This has been the case, for instance, of the thermal properties of the building envelope's transparent components, considered the rather high degree of uncertainty about their effective characteristics. Finally, also the climatic data (seasonal temperatures and humidity variations, solar radiation) corresponds to the contemporary definitions of the technical norms and standards: the definition of these parameters only requires the correct definition of the geographical position of the building being assessed.

Building envelope
INPUT MATERIAL/COMPONENTS PROPERTIES DATABASE

Database	Description
UNI 10351:2015	Materiali e prodotti per edilizia. Proprietà termoigrometriche. Procedura per la scelta dei valori di progetto.
UNI 10355:1994	Murature e solai. Valori della resistenza termica e metodo di calcolo.
UNI EN ISO 6946:2018	Componenti ed elementi per edilizia. Resistenza termica e trasmittanza termica. Metodo di calcolo.
TABULA WebTool	http://webtool.building-typology.eu/

Building envelope
INPUT MATERIAL/COMPONENTS PROPERTIES DATABASE

Database	Description
UNI 10349-1:2016	Riscaldamento e raffrescamento degli edifici. Dati climatici, Parte 1: Medie mensili per la valutazione della prestazione termo-energetica dell'edificio e metodi per ripartire l'irradianza solare nella frazione diretta e diffusa e per calcolare l'irradianza solare su di una superficie inclinata.

Definition of the building envelope

Objective of the analysis of the existing building envelope is to define its performance level, with respect of the actual requirements specified by the contemporary national standards.[01] In order to perform these evaluations, the building has been divided in two thermal zones, according to their destination. The INA-Casa towers, and the case study in Via Castelgomberto 35, are 9 storeys high, of which the upper 8 storeys destined to residential purposes, whilst the ground floor and mezzanine levels are destined to the commercial activities. The boundary of the thermal zones is the building envelope.

In a second stage, the different components of the building envelope have been scheduled, in order to define their dimensions and physical properties. The components must be classified according to their function:

- Vertical opaque components (towards exterior)
- Vertical transparent components (towards exterior)
- Horizontal opaque components (roof)
- Other horizontal opaque components (towards exterior)
- Partitions (horizontal/vertical, towards non-conditioned volumes)

In order to simplify the operation of collection of the geometric informations and their consistency and coordination, the architectural model realised in Revit 2020 has been exported in Rhino 6, providing the general shape and dimension of elements (measured on the outer boundary level towards the exterior). These information have been organised and elaborated in an Excel calculation sheet. The thermal and moisture evaluation of each individual components constitutes the initial stage of the process. The objective is to define the seasonal energy demand for heating and cooling ($EP_{H,nd}$, $EP_{C,nd}$) and the performance indexes H'_T and $A_{sol,est}/A_{sup,ut}$.

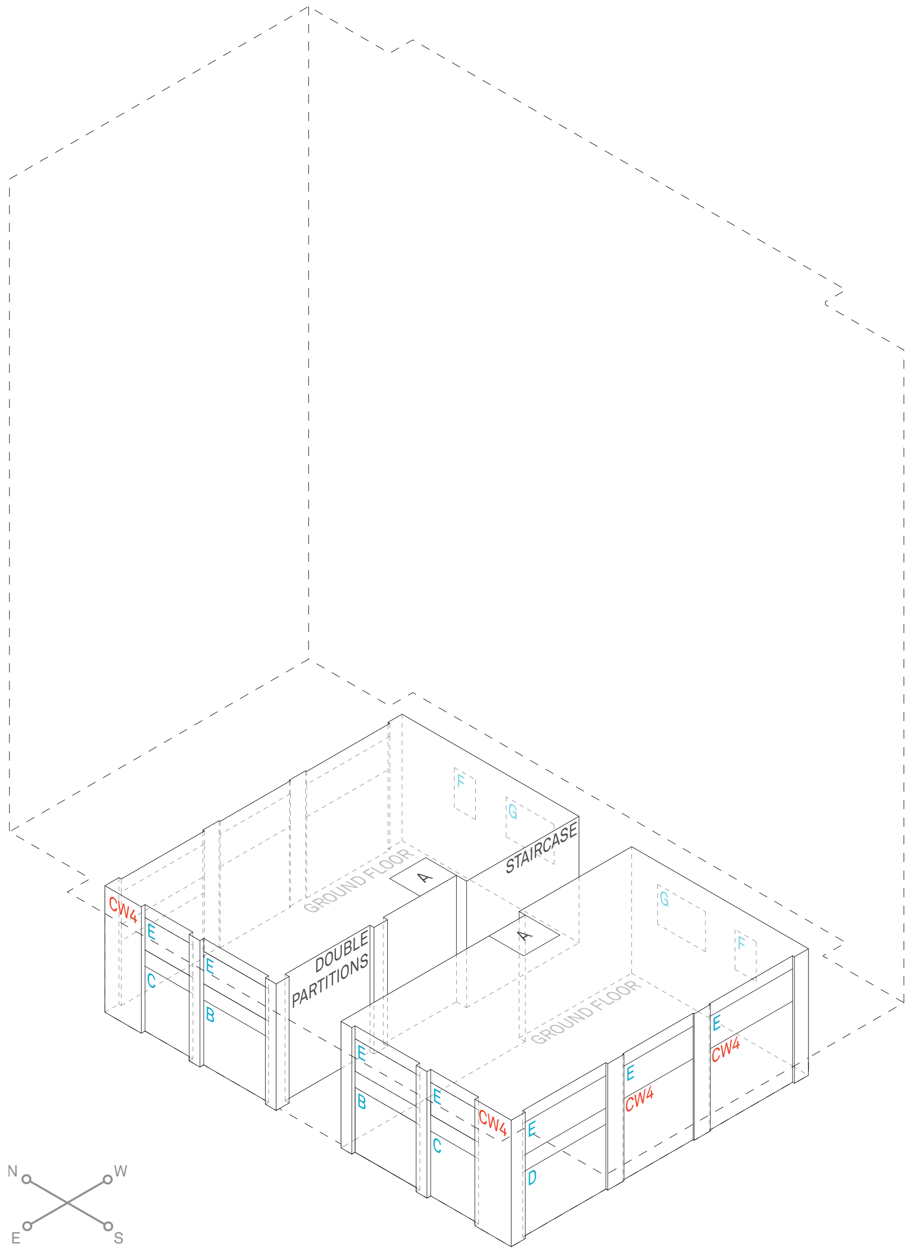
[01] D.M. 26 giugno 2015, in materia di "*Adeguamento del decreto del Ministro dello sviluppo economico, 26 giugno 2009 - Linee guida nazionali per la certificazione energetica degli edifici.*"

Building envelope
THERMAL ZONE 1

DESTINATION: commercial

Conditioned volume (V): 1089 m^3
Conditioned net floor area: 189 m^2
Envelope area (S): 683 m^2
Glazed area: 103 m^2
Compactness factor (S/V): 0.63 m^{-1}

Mean thermal capacity: 38392 kJ/K
Thermal time constant: 11.53 h



GROUND FLOOR

Vertical opaque

Component: CW4
Area: 215.8 m^2

Vertical transparent

Windows
Area: 56.3 m^2

Storefronts
Area: 46.9 m^2

Partitions

Ground floor
Area: 214.8 m^2

Staircase
Area: 52.7 m^2

Double partition
Area: 91.6 m^2

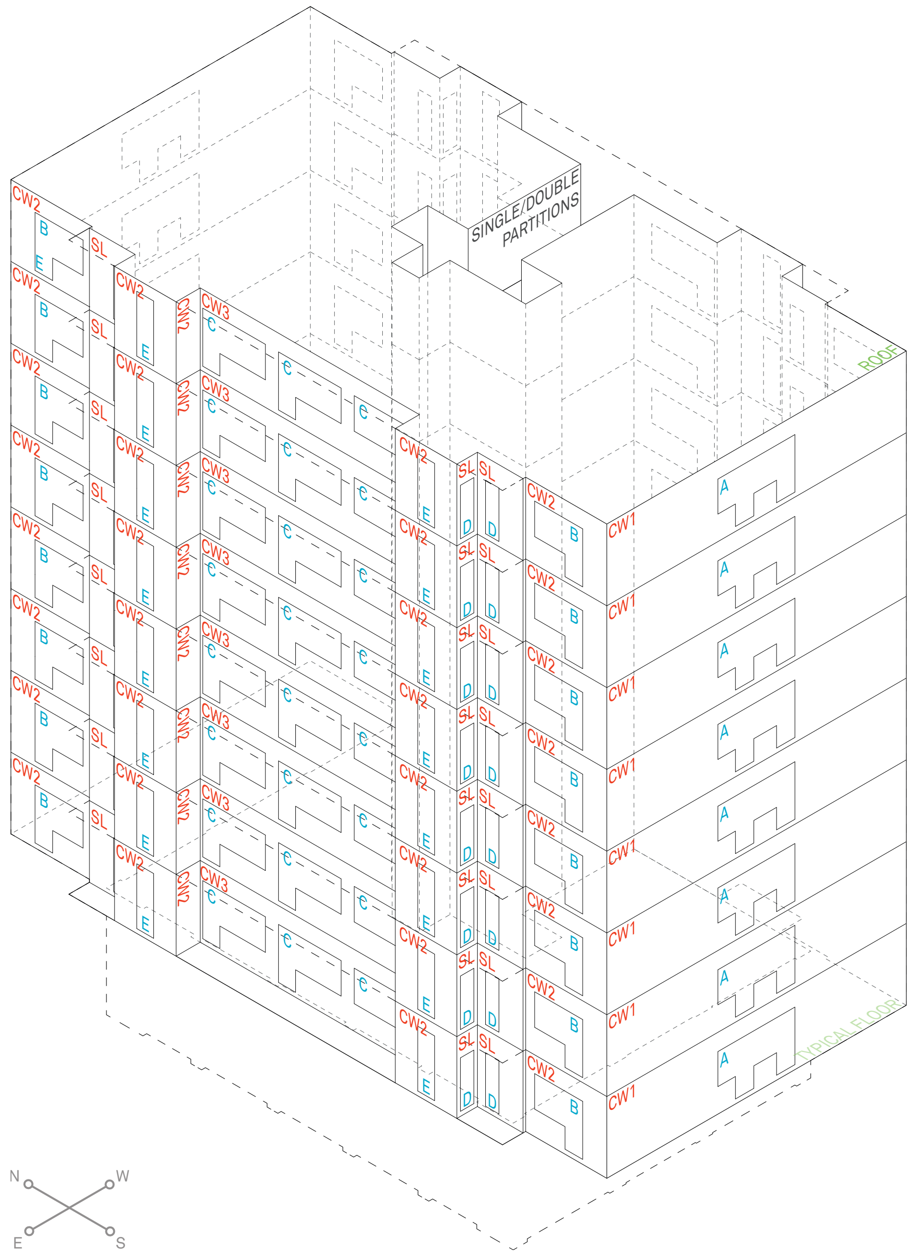
Typical floor (A)
Area: 19.4 m^2

Building envelope
THERMAL ZONE 2

DESTINATION: residential

Conditioned volume (V): 9639 m^3
Conditioned net floor area: 2504 m^2
Envelope area (S): 3550 m^2
Glazed area: 571 m^2
Compactness factor (S/V): 0.37 m^{-1}

Mean thermal capacity: 537786 kJ/K
Thermal time constant: 23.46 h



TYPICAL FLOOR

Vertical opaque

Component: CW1
Area: 77.5 m^2

Component: CW2
Area: 77.2 m^2

Component: CW3
Area: 34.2 m^2

Component: SL
Area: 31.0 m^2

Vertical transparent

Windows
Area: 71.4 m^2

Partitions

Single partition
Area: 61.2 m^2

Double partition
Area: 25.6 m^2

1st FLOOR

Horizontal opaque

Typical floor
Area: 139.5 m^2

Partitions

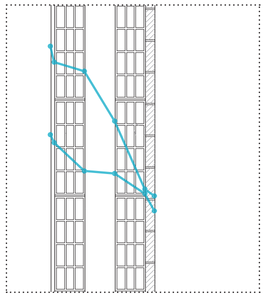
Typical floor (B)
Area: 19.4 m^2

9th FLOOR

Horizontal opaque

Roof
Area: 368.5 m^2

Components analysis
VERTICAL OPAQUE



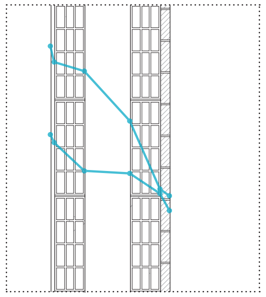
Layer	s [mm]	ρ [kg/m^3]	M_S [kg/m^2]	R_V [m^{2}sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m^{2}K/W]
INTERIOR							0,130
Finish	10	1200	12	0,0006	840	0,350	0,029
Structure	250	1800	187	0,0067	-	-	0,770
Cavity	80	1,3	-	0,0004	1000	0,026	0,180
Structure	80	1800	62	0,0021	-	-	0,200
Finish	20	1400	28	0,0011	840	0,700	0,029
EXTERIOR							0,040

CW1

R_{TOT} = 0.82 m^{2}K/W
U_{TOT} = 1.22 W/m^{2}K

M_S = 206 kg/m^2
Y_{ii} = 2.87 W/m^{2}K
Y_{ee} = 6.05 W/m^{2}K
Y_{ie} = 0.89 W/m^{2}K

k_i = 58.5 kJ/m^{2}K
k_e = 104.5 kJ/m^{2}K



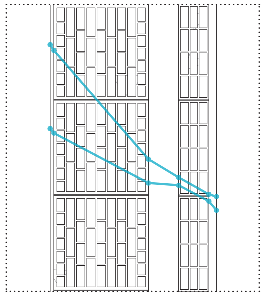
Layer	s [mm]	ρ [kg/m^3]	M_S [kg/m^2]	R_V [m^{2}sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m^{2}K/W]
INTERIOR							0,130
Finish	10	1200	12	0,0006	840	0,350	0,029
Structure	80	1800	62	0,0021	-	-	0,200
Cavity	120	1,30	-	0,0006	1000	0,026	0,180
Structure	80	1800	62	0,0021	-	-	0,200
Finish	35	2000	70	0,0013	840	0,900	0,039
EXTERIOR							0,040

CW2

R_{TOT} = 0.82 m^{2}K/W
U_{TOT} = 1.22 W/m^{2}K

M_S = 206 kg/m^2
Y_{ii} = 2.87 W/m^{2}K
Y_{ee} = 6.05 W/m^{2}K
Y_{ie} = 0.89 W/m^{2}K

k_i = 45.8 kJ/m^{2}K
k_e = 91.6 kJ/m^{2}K



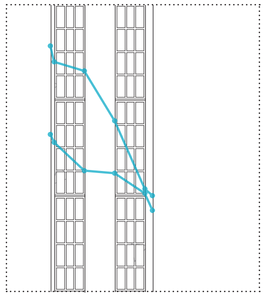
Layer	s [mm]	ρ [kg/m^3]	M_S [kg/m^2]	R_V [m^{2}sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m^{2}K/W]
INTERIOR							0,130
Finish	10	1200	12	0,0006	840	0,350	0,029
Structure	250	1800	187	0,0067	-	-	0,770
Cavity	80	1,3	-	0,0004	1000	0,026	0,180
Structure	80	1800	62	0,0021	-	-	0,200
Finish	20	1400	28	0,0011	840	0,700	0,029
EXTERIOR							0,040

CW3

R_{TOT} = 1.38 m^{2}K/W
U_{TOT} = 0.73 W/m^{2}K

M_S = 289 kg/m^2
Y_{ii} = 2.90 W/m^{2}K
Y_{ee} = 4.42 W/m^{2}K
Y_{ie} = 0.22 W/m^{2}K

k_i = 42.8 kJ/m^{2}K
k_e = 63.5 kJ/m^{2}K



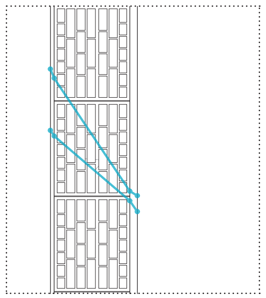
Layer	s [mm]	ρ [kg/m^3]	M_S [kg/m^2]	R_V [m^{2}sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m^{2}K/W]
INTERIOR							0,130
Finish	10	1200	12	0,0006	840	0,350	0,029
Structure	80	1800	62	0,0021	-	-	0,200
Cavity	80	1,3	-	0,0004	1000	0,026	0,180
Structure	80	1800	62	0,0021	-	-	0,200
Finish	20	1400	28	0,0011	840	0,700	0,029
EXTERIOR							0,040

CW4

R_{TOT} = 0.81 m^{2}K/W
U_{TOT} = 1.24 W/m^{2}K

M_S = 164 kg/m^2
Y_{ii} = 2.86 W/m^{2}K
Y_{ee} = 4.35 W/m^{2}K
Y_{ie} = 0.95 W/m^{2}K

k_i = 44.5 kJ/m^{2}K
k_e = 67.2 kJ/m^{2}K



Layer	s [mm]	ρ [kg/m^3]	M_S [kg/m^2]	R_V [m^{2}sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m^{2}K/W]
INTERIOR							0,130
Finish	10	1200	12	0,0006	840	0,350	0,029
Structure	200	1400	164	0,0064	-	-	0,470
Finish	20	1400	28	0,0011	840	0,700	0,029
EXTERIOR							0,040

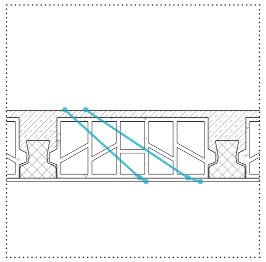
SL

R_{TOT} = 0.70 m^{2}K/W
U_{TOT} = 1.43 W/m^{2}K

M_S = 204 kg/m^2
Y_{ii} = 3.09 W/m^{2}K
Y_{ee} = 4.73 W/m^{2}K
Y_{ie} = 0.96 W/m^{2}K

k_i = 48.6 kJ/m^{2}K
k_e = 73.2 kJ/m^{2}K

Components analysis
HORIZONTAL OPAQUE



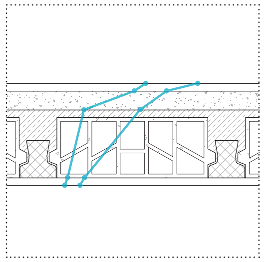
Layer	s [mm]	ρ [kg/m^3]	M_S [kg/m^2]	R_V [m^{2}sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m^{2}K/W]
INTERIOR							0,100
Finish	10	1200	12	0,0006	840	0,350	0,029
Structure	180	1800	171	0,0067	840	-	0,300
EXTERIOR							0,040

ROOF

R_{TOT} = 0.47 m^{2}K/W
U_{TOT} = 2.13 W/m^{2}K

Y_{ii} = 3.65 W/m^{2}K
Y_{ee} = 2.59 W/m^{2}K
Y_{ie} = 1.71 W/m^{2}K

k_i = 52.3 kJ/m^{2}K
k_e = 69.2 kJ/m^{2}K



Layer	s [mm]	ρ [kg/m^3]	M_S [kg/m^2]	R_V [m^{2}sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m^{2}K/W]
INTERIOR							0,170
Finish	20	710	14	0,0044	2400	0,180	0,111
Substrate	60	1500	90	0,0207	880	0,570	0,105
Structure	180	1800	171	0,0067	840	-	0,300
Finish	20	1400	28	0,0011	840	0,700	0,029
EXTERIOR							0,040

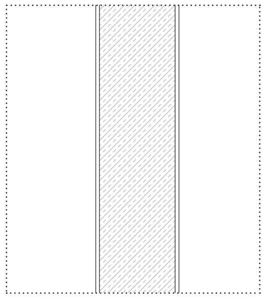
TYPICAL FLOOR

R_{TOT} = 0.75 m^{2}K/W
U_{TOT} = 1.32 W/m^{2}K

Y_{ii} = 3.04 W/m^{2}K
Y_{ee} = 5.41 W/m^{2}K
Y_{ie} = 0.52 W/m^{2}K

k_i = 47.5 kJ/m^{2}K
k_e = 81.0 kJ/m^{2}K

Components analysis
VERTICAL PARTITIONS



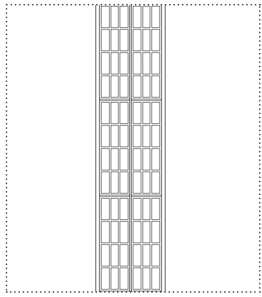
Layer	s [mm]	ρ [kg/m^3]	M_S [kg/m^2]	R_V [m^{2}sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m^{2}K/W]
INTERIOR							0,130
Finish	10	1200	12	0,0006	840	0,350	0,029
Substrate	250	2200	550	0,0862	880	1,480	0,169
Finish	10	1200	12	0,0006	840	0,350	0,029
EXTERIOR							0,130

STAIRCASE

R_{TOT} = 0.49 m^{2}K/W
U_{TOT} = 2.06 W/m^{2}K

Y_{ii} = 4.83 W/m^{2}K
Y_{ee} = 4.83 W/m^{2}K
Y_{ie} = 0.52 W/m^{2}K

k_i = 71.7 kJ/m^{2}K
k_e = 71.7 kJ/m^{2}K



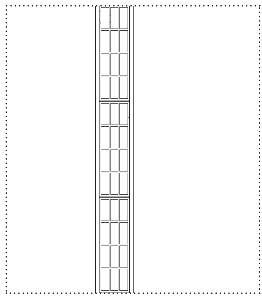
Layer	s [mm]	ρ [kg/m^3]	M_S [kg/m^2]	R_V [m^{2}sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m^{2}K/W]
INTERIOR							0,130
Finish	10	1200	12	0,0006	840	0,350	0,029
Structure	80	1800	62	0,0862	880	1,480	0,169
Finish	10	1200	12	0,0006	840	0,350	0,029
EXTERIOR							0,130

SINGLE PARTITION

R_{TOT} = 0.52 m^{2}K/W
U_{TOT} = 1.93 W/m^{2}K

Y_{ii} = 2.72 W/m^{2}K
Y_{ee} = 2.72 W/m^{2}K
Y_{ie} = 1.76 W/m^{2}K

k_i = 33.0 kJ/m^{2}K
k_e = 33.0 kJ/m^{2}K



Layer	s [mm]	ρ [kg/m^3]	M_S [kg/m^2]	R_V [m^{2}sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m^{2}K/W]
INTERIOR							0,130
Finish	10	1200	12	0,0006	840	0,350	0,029
Substrate	80	1800	62	0,0021	-	-	0,200
Structure	80	1800	62	0,0021	-	-	0,200
Finish	10	1200	12	0,0006	840	0,350	0,029
EXTERIOR							0,130

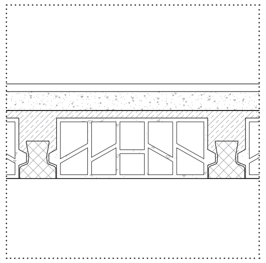
DOUBLE PARTITION

R_{TOT} = 0.72 m^{2}K/W
U_{TOT} = 1.39 W/m^{2}K

Y_{ii} = 2.99 W/m^{2}K
Y_{ee} = 2.99 W/m^{2}K
Y_{ie} = 0.99 W/m^{2}K

k_i = 45.5 kJ/m^{2}K
k_e = 45.5 kJ/m^{2}K

Components analysis
HORIZONTAL PARTITIONS

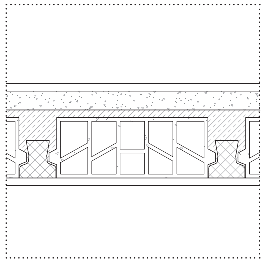


Layer	s [mm]	ρ [kg/m³]	M_s [kg/m²]	R_v [m²sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m²K/W]
INTERIOR							0,170
Finish	20	2300	46	0,0213	840	0,940	0,021
Substrate	60	1500	90	0,0207	880	0,570	0,105
Structure	180	1800	171	0,0067	-	-	0,300
EXTERIOR							0,040

GROUND FLOOR
R_{TOT} = 0.64 m²K/W
U_{TOT} = 1.57 W/m²K

Y_{ii} = 3.90 W/m²K
Y_{ee} = 4.98 W/m²K
Y_{ie} = 0.74 W/m²K

k_i = 60.3 kJ/m²K
k_e = 76.7 kJ/m²K

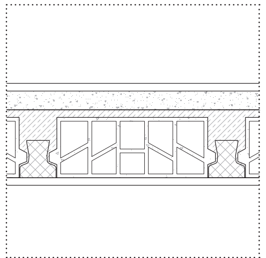


Layer	s [mm]	ρ [kg/m³]	M_s [kg/m²]	R_v [m²sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m²K/W]
INTERIOR							0,100
Finish	20	1400	28	18,00	840	0,700	0,029
Structure	180	1800	171	26,79	840	-	0,300
Substrate	60	1500	90	2,90	880	0,570	0,105
Finish	20	710	14	4,50	2400	0,180	0,111
EXTERIOR							0,040

TYPICAL FLOOR (A)
R_{TOT} = 0.68 m²K/W
U_{TOT} = 1.46 W/m²K

Y_{ii} = 4.26 W/m²K
Y_{ee} = 4.73 W/m²K
Y_{ie} = 0.63 W/m²K

k_i = 66.0 kJ/m²K
k_e = 72.7 kJ/m²K



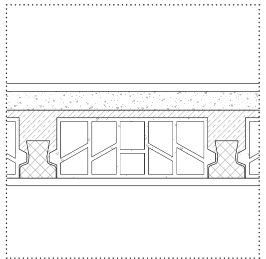
Layer	s [mm]	ρ [kg/m³]	M_s [kg/m²]	R_v [m²sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m²K/W]
INTERIOR							0,170
Finish	20	710	14	0,0044	2400	0,180	0,111
Substrate	60	1500	90	0,0207	880	0,570	0,105
Structure	180	1800	171	0,0067	840	-	0,300
Finish	20	1400	28	0,0011	840	0,700	0,029
EXTERIOR							0,040

TYPICAL FLOOR (B)
R_{TOT} = 0.75 m²K/W
U_{TOT} = 1.32 W/m²K

Y_{ii} = 3.04 W/m²K
Y_{ee} = 5.41 W/m²K
Y_{ie} = 0.52 W/m²K

k_i = 47.5 kJ/m²K
k_e = 81.0 kJ/m²K

Components analysis
HORIZONTAL PARTITIONS (TOWARDS CONDITIONED SPACES)



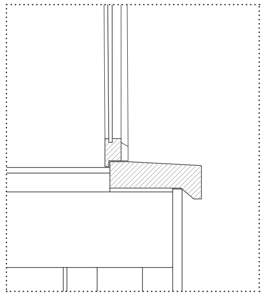
Layer	s [mm]	ρ [kg/m³]	M_s [kg/m²]	R_v [m²sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m²K/W]
INTERIOR							0,130
Finish	20	710	14	0,0044	2400	0,180	0,111
Substrate	60	1500	90	0,0207	880	0,570	0,105
Structure	180	1800	171	0,0067	840	-	0,300
Finish	20	1400	28	0,0011	840	0,700	0,029
EXTERIOR							0,130

TYPICAL FLOOR (B)
R_{TOT} = 0.80 m²K/W
U_{TOT} = 1.24 W/m²K

Y_{ii} = 3.43 W/m²K
Y_{ee} = 3.83 W/m²K
Y_{ie} = 0.41 W/m²K

k_i = 52.3 kJ/m²K
k_e = 57.9 kJ/m²K

Components analysis
TRANSPARENT



Layer	$g_{gl,n}$ [-]	$g_{gl+sh}/g_{gl,n}$ [-]	ξ [-]	Shutter	ΔR [m²K/W]
Single pane + Frame	0.85	1	0.837	Wood/Plastics (without foam)	0.16

WINDOWS
U_{W+shut} = 2.75 W/m²K
U_W = 4.90 W/m²K

Layer	$g_{gl,n}$ [-]	$g_{gl+sh}/g_{gl,n}$ [-]	ξ [-]	Shutter	ΔR [m²K/W]
Single pane + Frame	0.85	1	0.837	Wood/Plastics (without foam)	0.16

STOREFRONTS
U_{W+shut} = 2.75 W/m²K
U_W = 4.90 W/m²K

Components analysis
CLIMATIC DATA INPUT (TURIN)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
θ_e [°C]	1,3	3,2	8,4	12,0	18,1	22,2	23,7	22,7	19,2	12,4	6,9	2,7
$p_{vs,e}$ [Pa]	671	768	1102	1402	1402	2675	2929	2757	2224	1439	994	741
p_e [Pa]	558	618	888	934	1355	1616	1584	2003	1659	1180	925	654
ϕ_e [%]	83%	80%	81%	67%	97%	60%	54%	73%	75%	82%	93%	88%
θ_i [OC]	20,0	20,0	20,0	20,0	18,1	22,2	23,7	22,7	19,2	20,0	20,0	20,0
Δp [Pa]	764	696	512	384	167	100	100	100	128	370	565	714
$p_{vs,i}$ [Pa]	2337	2337	2337	2337	1402	2675	2929	2757	2224	2337	2337	2337
p_i [Pa]	1322	1314	1400	1318	1522	1716	1684	2103	1787	1550	1490	1368
ϕi [%]	57%	56%	60%	56%	109%	64%	57%	76%	80%	66%	64%	59%
$p_{vs,max}$ [Pa]	1652	1643	1750	1648	1903	2145	2105	2629	2234	1475	1863	1710
$\theta_{si,min}$ [OC]	14,3	14,3	15,2	14,3	16,6	18,6	18,2	21,8	19,1	16,8	16,2	14,9
$f_{Rsi,min}$ [-]	0,70	0,66	0,59	0,29	0,00	0,00	0,00	0,00	0,00	0,58	0,71	0,71

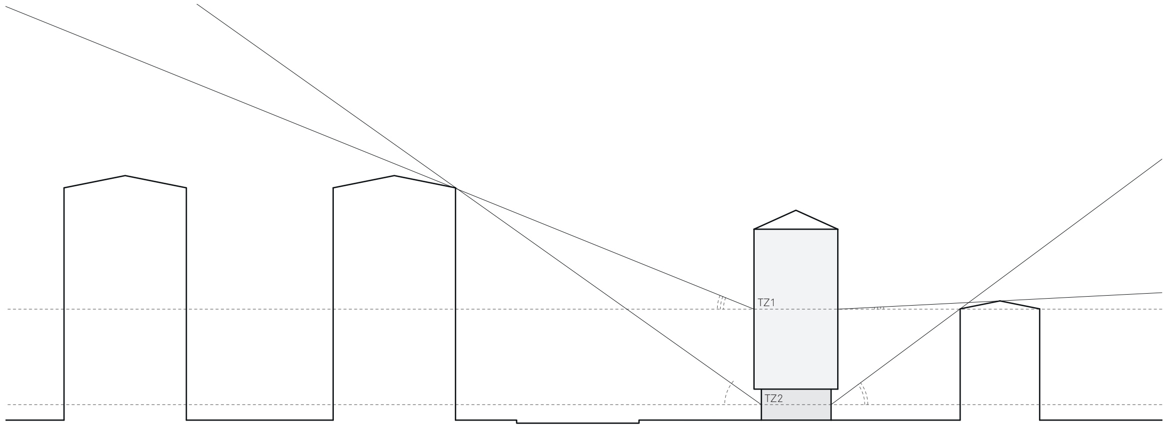
Evaluation of performance and energy efficiency

Once that the envelope components have been broke down and analysed individually, it is possible, knowing their properties, to evaluate both the general performance of the building envelope and the energy demand for heating and cooling. The definition of the energy demand requires, as input parameters, the heat exchange contribution of each technological component (sum of its surfaces relative to the thermal zone of interest multiplied by the thermal transmittance). This process is specific for each thermal zones, hence two different calculation sheets were necessary. In this stage, it had been necessary to evaluate the impact and heat transfer of thermal bridges. Their values have been retrieved from a national database of functional components and their typical arrangement.[02] Secondly, another important aspect to take care of is the definition of the external shading characteristics of the building: these regard both external obstructions (i.e. other buildings) and horizontal of vertical obstructions, which can be both due to the plan configuration, to balconies or proper shading fixed devices. In this case study, the relevance of external obstructions is poor, while more important is that of horizontal and vertical shading, due to the balconies and cantilevers on the east and west facade. Finally, it must be measured the thermal capacity of each thermal zone, which includes the contribution of the interior surfaces (such as those of partition walls).

The evaluation of performance is, on the other hand, general for the entire building: no distinction is made between the thermal zones, hence its values provide an immediate hint about the global behaviour of the envelope. Two parameters have been calculated: the global average heat transfer coefficient (H'_T) (which normalises the global heat transfer by the envelope surface) and the summer equivalent solar area (normalised by the floor net area) ($A_{sol,est}$ / $A_{sup,ut}$). This values have been confronted with the requirements of the energy efficiency requirements regulations and as the main design parameters for the retrofit proposal.

[02] Corrado, V. (2011). *Atlante nazionale dei ponti termici: conforme alle norme UNI EN ISO 14683 e UNI EN ISO 10211*. 1st ed. Borgomanero: Edizioni Edilclima.

External shading
TERRITORIAL SECTION E/W



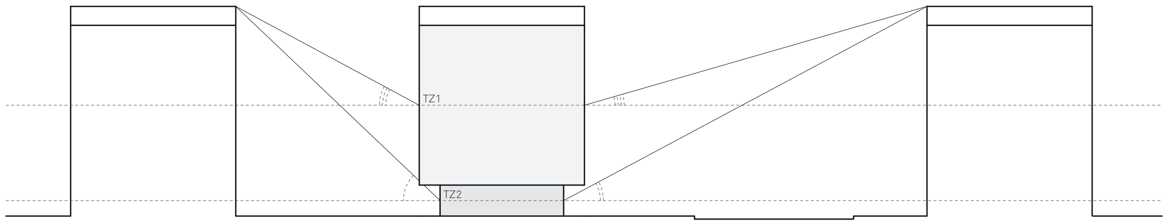
Heat transfer
THERMAL ZONE 1

VERTICAL OPAQUE	A [m²]	U [W/m²K]	Orientation	$b_{tr,x}$	$F_{sh,ob,dif}$ [-]	$a_{sol,c}$ [-]	ξ [-]
CW4	47,6	1,24	S	1,0	0,34	0,60	0,90
CW4	47,6	1,24	N	1,0	0,25	0,60	0,90
CW4	72,4	1,24	E	1,0	0,30	0,60	0,90
CW4	47,9	1,24	W	1,0	0,30	0,60	0,90
HORIZONTAL OPAQUE	**A [m²]**	**U [W/m²K]**	**Orientation**	**$b_{tr,x}$**	**$F_{sh,ob,dif}$ [-]**	**$a_{sol,c}$ [-]**	**ξ [-]**
GROUND FLOOR	214,8	1,57	-	0,5	-	-	-
PARTITIONS	**A [m²]**	**U [W/m²K]**	**Orientation**	**$b_{tr,x}$**	**$F_{sh,ob,dif}$ [-]**	**$a_{sol,c}$ [-]**	**ξ [-]**
STAIRCASE	52,7	2,06	-	0,6	-	-	-
DOUBLE PARTITION	91,6	1,39	-	0,6	-	-	-
TYPICAL FLOOR (A)	5,0	1,46	-	0,6	-	-	-

TRANSPARENT	A [m²]	U_W	U_{W+SH}	Orientation	$b_{tr,x}$	$F_{sh,ob,dif}$ [-]	F_F [-]	$g_{gl,n}$ [-]	g_{gl+sh} [-]	ξ [-]
B	15,56	4,90	2,75	E/W	1,0	0,30	0,28	0,85	0,80	0,837
C	11,42	4,90	2,75	E/W	1,0	0,30	0,28	0,85	0,80	0,837
D	9,95	4,90	2,75	S	1,0	0,34	0,27	0,85	0,71	0,837
D	9,95	4,90	2,75	N	1,0	0,25	0,27	0,85	0,75	0,837
E	17,72	4,90	2,75	E/W	1,0	0,30	0,17	0,85	0,80	0,837
E	14,20	4,90	2,75	S	1,0	0,34	0,14	0,85	0,71	0,837
E	14,20	4,90	2,75	N	1,0	0,25	0,14	0,85	0,75	0,837
F	3,14	4,90	2,75	E/W	1,0	0,30	0,22	0,85	0,80	0,837
G	7,09	4,90	2,75	E/W	1,0	0,30	0,15	0,85	0,80	0,837

THERMAL BRIDGE	L [m]	ψ [W/mK]	Orientation	$b_{tr,x}$	Description
B4	62,2	0,46	-	1,00	Balcony
C4	50,7	-0,60	-	0,92	Corner (concave)
C8	10,1	0,24	-	0,60	Corner (convex)
GF4	90,6	0,16	-	0,87	Connection to ground
IF4	28,5	0,49	-	0,60	Interstorey floor
P4	111,5	0,59	-	0,89	Pillars
R4	0,0	0,04	-	1,00	Roof
W10	183,7	0,12	-	1,00	Windows

External shading
TERRITORIAL SECTION N/S



Heat transfer
THERMAL ZONE 2

VERTICAL OPAQUE	A [m²]	U [W/m²K]	Orientation	$b_{tr,x}$	$F_{sh,ob,dif}$ [-]	$a_{sol,c}$ [-]	ξ [-]
CW1	309,9	1,22	S	1,0	0,52	0,90	0,90
CW1	309,9	1,22	N	1,0	0,67	0,90	0,90
CW2	58,4	1,22	S	1,0	0,52	0,90	0,90
CW2	58,4	1,22	N	1,0	0,67	0,90	0,90
CW2	500,6	1,22	E/W	1,0	0,83	0,90	0,90
CW3	124,0	0,73	E	1,0	0,83	0,30	0,90
CW3	149,3	0,73	W	1,0	0,56	0,30	0,90
SL	28,5	1,43	S	1,0	0,37	0,30	0,90
SL	28,5	1,43	N	1,0	0,48	0,30	0,90
SL	190,9	1,43	E/W	1,0	0,66	0,30	0,90
HORIZONTAL OPAQUE	**A [m²]**	**U [W/m²K]**	**Orientation**	**$b_{tr,x}$**	**$F_{sh,ob,dif}$ [-]**	**$a_{sol,c}$ [-]**	**ξ [-]**
ROOF	368,5	2,13	-	0,8	-	-	-
TYPICAL FLOOR (EXT)	139,5	1,32	-	1,0	-	-	-
PARTITIONS	**A [m²]**	**U [W/m²K]**	**Orientation**	**$b_{tr,x}$**	**$F_{sh,ob,dif}$ [-]**	**$a_{sol,c}$ [-]**	**ξ [-]**
SINGLE PARTITION	489,2	1,93	-	0,6	-	-	-
DOUBLE PARTITION	204,8	1,39	-	0,6	-	-	-
TYPICAL FLOOR (B)	19,4	1,32	-	0.6	-	-	-

TRANSPARENT	A [m²]	U_W	U_{W+SH}	Orientation	$b_{tr,x}$	$F_{sh,ob,dif}$ [-]	F_F [-]	$g_{gl,n}$ [-]	g_{gl+sh} [-]	ξ [-]
A	52,08	4,90	2,75	S	1,0	0,52	0,46	0,85	0,71	0,837
A	52,08	4,90	2,75	N	1,0	0,67	0,46	0,85	0,75	0,837
B	62,08	4,90	2,75	E	1,0	0,74	0,46	0,85	0,80	0,837
B	62,08	4,90	2,75	W	1,0	0,83	0,46	0,85	0,80	0,837
C	192,80	4,90	2,75	E/W	1,0	0,66	0,45	0,85	0,80	0,837
D	21,28	4,90	2,75	S	1,0	0,37	0,35	0,85	0,71	0,837
D	21,28	4,90	2,75	N	1,0	0,48	0,35	0,85	0,75	0,837
D	42,56	4,90	2,75	E/W	1,0	0,66	0,35	0,85	0,80	0,837
E	64,64	4,90	2,75	E/W	1,0	0,83	0,43	0,85	0,80	0,837

THERMAL BRIDGE	L [m]	ψ [W/mK]	Orientation	$b_{tr,x}$	Description
B4	310,7	0,46	-	1,00	Balcony
C4	680,2	-0,60	-	0,91	Corner (concave)
C8	470,9	0,24	-	0,87	Corner (convex)
IF	648,4	0,49	-	0,87	Interstorey floor
P4	627,8	0,59	-	0,93	Pillars
R4	81,0	0,04	-	0,93	Roof
W10	1514,3	0,12	-	1,00	Windows

Performance index of the building envelope
SUMMER EQUIVALENT SOLAR AREA ($A_{sol,est}/A_{sup,ut}$)

THERMAL ZONE 1		THERMAL ZONE 2	
COMPONENT	$A_{sol,es}$ [m²]	COMPONENT	$A_{sol,es}$ [m²]
B	3,42	A	10,40
C	2,51	A	-
D	2,69	B	23,14
D	-	B	23,14
E	4,49	C	73,21
E	4,51	D	5,11
E	-	D	-
F	0,75	D	16,62
G	1,84	E	25,44
$A_{sol,est}$ [m²]	**20,19**	$A_{sol,est}$ [m²]	**177,07**

PRE-RETROFIT
$A_{sol,est}$ = 197.26 m²
$A_{sup,ut}$ = 2243 m²
$A_{sol,est}/A_{sup,ut}$ = 0.088

Performance index of the building envelope
GLOBAL AVERAGE HEAT TRANSFER COEFFICIENT (H'_T)

COMPONENT	THERMAL ZONE 1	THERMAL ZONE 2
	H [W/K]	H [W/K]
VERTICAL OPAQUE	267,0	2067,4
HORIZONTAL OPAQUE	168.4	818,2
PARTITIONS	145,2	754,3
TRANSPARENT	372,5	2059,7
THERMAL BRIDGES	103,6	675,5
$H_{tr,adj}$ [W/K]	**1056,7**	**6375,1**

PRE-RETROFIT
$H_{tr,adj}$ = 7431.8 W/K
S = 4234 m²
H'_T = 1.76 W/m²K

These results show how the existing construction, in its actual state, is very far from the actual performance standards. A major renovation of the existing building, in particular a renovation of first level, can enhance dramatically the properties of the envelope, consequently reducing the amount of energy needed for seasonal heating and cooling, which account, in average, for the largest amount of energy consumptions (in particular in respect to residential destinations, as the main function of the case study).

Energy retrofit strategy

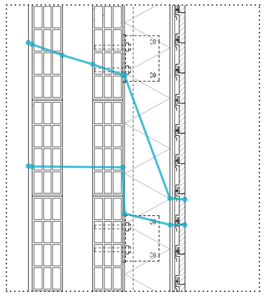
The process of performance and energy demand assessment of the existing building has been used as a basis for the definition of the retrofit strategy. As a new skin for the deep renovation, the exoskeleton allows to redesign almost completely the physical behaviour of the building, hence it falls in the major renovation of the first level casuistry. The performance requirements are connected to this consideration: for this class of operations, the standards to be achieved are comparable to those valid for new NZEB constructions.

In first place, it was necessary to quantify the amount of thermal insulation that the existing components would need, in order to comply with the contemporary requirements. Although these do not constitute a mandatory requirement, the values of the reference building provided by the D.M. have been considered in the design of the insulation as a target level of performance of the single components. The general envelope renovation strategy is aimed at protecting the original massive elements (prior demolition of the existing coating or cladding materials) while letting the exoskeleton as a cold, non conditioned space. On the east and west side, however, the exoskeleton will host external winter gardens: these spaces, although not being as insulated as the interior spaces, are considered as buffer volumes (or sun spaces). The rather low degree of external obstructions guarantees the availability of a relevant amount of sunlight in winter months. At the same time, the additional shading should protect against overheating in summer. The influence of these buffer volume is exemplified, in the evaluation of the envelope's performance, as a reduction factor for the heat transfer of the facade walls (b_{tr}). On a technological level, the sun spaces are conceived as closed cavity buffers, spanning from one floor to the other. The space is assumed as enclosed in winter and opened in summer, when the additional volumes act only as horizontal shaders.

Given these considerations, the achievement of a proper degree of insulation of each component is fundamental to fulfill the above mentioned requirements and is in fact the first stage of the retrofit design. Furthermore, particular attention must be addressed to the technological detail: by employing a continuous external insulation layer and thermal breaks as connection devices for the steel exoskeleton frame, the impact of most of the existing thermal bridges removed, with a great impact on the overall energy performance. The only critical points that have been considered are the connection to ground and the interstory connections in the non-conditioned common spaces (i.e. underground floor and stairwell). The insulation of vertical and horizontal partitions towards non conditioned spaces would be the only operation to be carried out in the interior spaces. For this purpose, in order to reduce the impact of such operations, materials with higher performance have been chosen. Characteristic values of the new layers are gathered from the technical documentation provided by the materials' manufacturer.

Finally, the objective of this analysis is to compare the pre and post-retrofit H'_T and $A_{sol,est}/A_{sup,ut}$ indexes and energy demand for heating and cooling are compared with the existing building and with the actual standards for major renovations. The scope of the joint work on structural and energy retrofit, in fact, is to provide a post-retrofit situation that is all in all comparable to the level of performance of a new construction. It is under this premise that it is possible to compare the eventuality of a demolition and reconstruction, and that of a deep, integrate retrofit intervention by means of the adaptive exoskeleton methodological approach. The results show how it is possible, with the addition of new technologies, to achieve an up to date level of performance by adapting the building from the outside in.

Retrofit: components analysis
VERTICAL OPAQUE



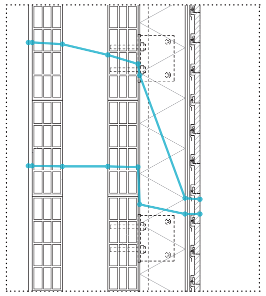
Layer	s $[mm]$	ρ $[kg/m^3]$	M_S $[kg/m^2]$	R_V $[m^2sPa/kg]$	c $[J/kgK]$	λ $[J/kgK]$	R_i $[m^2K/W]$
INTERIOR							0,130
Existing	250	-	12	0,0053	840	-	0,609
Vapour barrier	0,22	500	0,11	0,2000	1800	0,400	0,001
Insulation	120	32	3,84	0,0480	1700	0,036	3,333
Finish	35	2000	70	0,0013	840	0,900	0,039
EXTERIOR							0,040

CW1

R_{TOT} = 4.15 m²K/W
U_{TOT} = 0.24 W/m²K

M_S = 210 kg/m²
Y_{ii} = 3.10 W/m²K
Y_{ee} = 4.23 W/m²K
Y_{ie} = 0.08 W/m²K

k_i = 43.7 kJ/m²K
k_e = 59.5 kJ/m²K



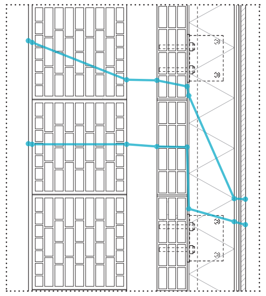
Layer	s $[mm]$	ρ $[kg/m^3]$	M_S $[kg/m^2]$	R_V $[m^2sPa/kg]$	c $[J/kgK]$	λ $[J/kgK]$	R_i $[m^2K/W]$
INTERIOR							0,130
Existing	290	-	136	0,0053	-	-	0,609
Vapour barrier	0,22	500	0,11	0,2000	1800	0,400	0,001
Insulation	120	32	3,84	0,0480	1700	0,036	3,333
Finish	35	2000	70	0,0013	840	0,900	0,039
EXTERIOR							0,040

CW2

R_{TOT} = 4.15 m²K/W
U_{TOT} = 0.24 W/m²K

M_S = 210 kg/m²
Y_{ii} = 3.10 W/m²K
Y_{ee} = 4.23 W/m²K
Y_{ie} = 0.08 W/m²K

k_i = 43.7 kJ/m²K
k_e = 59.5 kJ/m²K



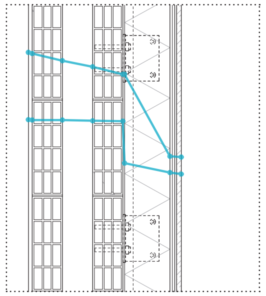
Layer	s $[mm]$	ρ $[kg/m^3]$	M_S $[kg/m^2]$	R_V $[m^2sPa/kg]$	c $[J/kgK]$	λ $[J/kgK]$	R_i $[m^2K/W]$
INTERIOR							0,130
Existing	420	-	261	0,0098	-	-	1,180
Vapour barrier	0,22	500	0,11	0,2000	1800	0,400	0,001
Insulation	120	32	3,84	0,0480	1700	0,036	3,333
Finish	12,5	1150	14	0,0041	880	0,350	0,036
EXTERIOR							0,040

CW3

R_{TOT} = 4.72 m²K/W
U_{TOT} = 0.21 W/m²K

M_S = 279 kg/m²
Y_{ii} = 2.89 W/m²K
Y_{ee} = 1.15 W/m²K
Y_{ie} = 0.02 W/m²K

k_i = 39.8 kJ/m²K
k_e = 15.3 kJ/m²K



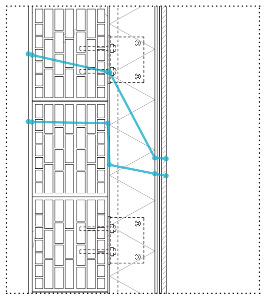
Layer	s $[mm]$	ρ $[kg/m^3]$	M_S $[kg/m^2]$	R_V $[m^2sPa/kg]$	c $[J/kgK]$	λ $[J/kgK]$	R_i $[m^2K/W]$
INTERIOR							0,130
Existing	290	-	136	0,0053	-	-	0,609
Vapour barrier	0,22	500	0,11	0,2000	1800	0,400	0,001
Insulation	120	32	3,84	0,0480	1700	0,036	3,333
Finish	12,5	1150	14	0,0041	880	0,350	0,036
EXTERIOR							0,040

CW4

R_{TOT} = 4.15 m²K/W
U_{TOT} = 0.24 W/m²K

M_S = 154 kg/m²
Y_{ii} = 3.10 W/m²K
Y_{ee} = 1.12 W/m²K
Y_{ie} = 0.08 W/m²K

k_i = 43.7 kJ/m²K
k_e = 16.4 kJ/m²K



Layer	s $[mm]$	ρ $[kg/m^3]$	M_S $[kg/m^2]$	R_V $[m^2sPa/kg]$	c $[J/kgK]$	λ $[J/kgK]$	R_i $[m^2K/W]$
INTERIOR							0,130
Existing	210	-	176	0,0073	-	-	0.329
Vapour barrier	0,22	500	0,11	0,2000	1800	0,400	0,001
Insulation	120	32	3,84	0,0480	1700	0,036	3,333
Finish	12,5	1150	14	0,0041	880	0,350	0,036
EXTERIOR							0,040

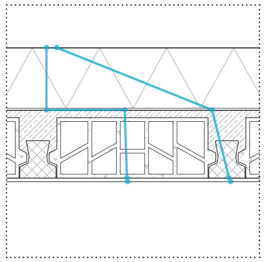
SL

R_{TOT} = 4.04 m²K/W
U_{TOT} = 0.25 W/m²K

M_S = 194 kg/m²
Y_{ii} = 3.28 W/m²K
Y_{ee} = 1.11 W/m²K
Y_{ie} = 0.07 W/m²K

k_i = 46.0 kJ/m²K
k_e = 16.2 kJ/m²K

Retrofit: components analysis
HORIZONTAL OPAQUE



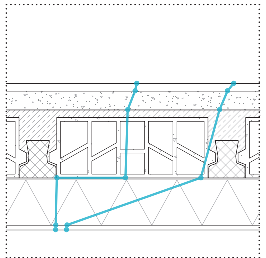
Layer	s $[mm]$	ρ $[kg/m^3]$	M_S $[kg/m^2]$	R_V $[m^2sPa/kg]$	c $[J/kgK]$	λ $[J/kgK]$	R_i $[m^2K/W]$
INTERIOR							0,100
Existing	190	-	193	0,0073	-	-	0,329
Vapour barrier	0,22	500	0,11	0,2000	1800	0,400	0,001
Insulation	160	150	24	0,0008	1030	0,038	4,211
EXTERIOR							0,040

ROOF

R_{TOT} = 4.68 m²K/W
U_{TOT} = 0.21 W/m²K

Y_{ii} = 4.18 W/m²K
Y_{ee} = 0.63 W/m²K
Y_{ie} = 0.06 W/m²K

k_i = 58.3 kJ/m²K
k_e = 9.3 kJ/m²K



Layer	s $[mm]$	ρ $[kg/m^3]$	M_S $[kg/m^2]$	R_V $[m^2sPa/kg]$	c $[J/kgK]$	λ $[J/kgK]$	R_i $[m^2K/W]$
INTERIOR							0,170
Existing	260	-	275	0,2181	-	-	0,516
V. barrier	0,22	500	0,11	0,2000	1800	0,400	0,001
Insulation	120	150	18	0,0006	1030	0,038	3,158
Finish	12,5	1150	14,38	0,0041	840	0,350	0,036
EXTERIOR							0,040

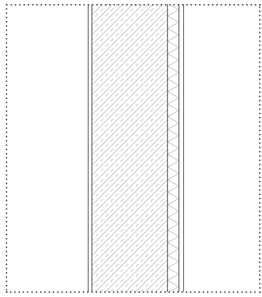
TYPICAL FLOOR

R_{TOT} = 3.92 m²K/W
U_{TOT} = 0.26 W/m²K

Y_{ii} = 3.03 W/m²K
Y_{ee} = 1.32 W/m²K
Y_{ie} = 0.03 W/m²K

k_i = 42.0 kJ/m²K
k_e = 18.3 kJ/m²K

Retrofit: components analysis
VERTICAL PARTITIONS



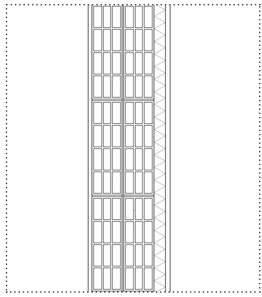
Layer	s $[mm]$	ρ $[kg/m^3]$	M_S $[kg/m^2]$	R_V $[m^2sPa/kg]$	c $[J/kgK]$	λ $[J/kgK]$	R_i $[m^2K/W]$
INTERIOR							0,130
Existing	260	-	562	0,0868	-	-	0,198
Insulation	30	50	2	0,0002	1030	0,035	0,857
Finish	12,5	900	11	0,0005	1090	0,210	0,060
EXTERIOR							0,130

STAIRCASE

R_{TOT} = 1.37 m²K/W
U_{TOT} = 0.73 W/m²K

Y_{ii} = 4.84 W/m²K
Y_{ee} = 1.23 W/m²K
Y_{ie} = 0.10 W/m²K

k_i = 67.7 kJ/m²K
k_e = 18.3 kJ/m²K



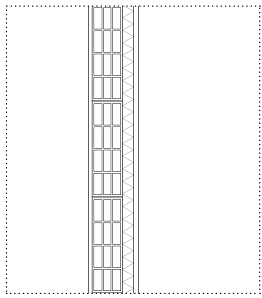
Layer	s $[mm]$	ρ $[kg/m^3]$	M_S $[kg/m^2]$	R_V $[m^2sPa/kg]$	c $[J/kgK]$	λ $[J/kgK]$	R_i $[m^2K/W]$
INTERIOR							0,130
Existing	90	-	74	0,0027	-	-	0,229
Insulation	30	50	2	0,0002	1030	0,035	0,857
Finish	12,5	900	11	0,0005	1090	0,210	0,060
EXTERIOR							0,130

SINGLE PARTITION

R_{TOT} = 1.41 m²K/W
U_{TOT} = 0.71 W/m²K

Y_{ii} = 2.99 W/m²K
Y_{ee} = 1.20 W/m²K
Y_{ie} = 0.56 W/m²K

k_i = 42.8 kJ/m²K
k_e = 18.8 kJ/m²K



Layer	s $[mm]$	ρ $[kg/m^3]$	M_S $[kg/m^2]$	R_V $[m^2sPa/kg]$	c $[J/kgK]$	λ $[J/kgK]$	R_i $[m^2K/W]$
INTERIOR							0,130
Existing	170	-	1134	0,0027	-	-	0,429
Insulation	30	50	2	0,0002	1030	0,035	0,857
Finish	12,5	900	11	0,0005	1090	0,210	0,060
EXTERIOR							0,130

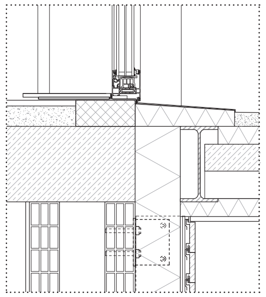
DOUBLE PARTITION

R_{TOT} = 1.61 m²K/W
U_{TOT} = 0.62 W/m²K

Y_{ii} = 3.26 W/m²K
Y_{ee} = 1.23 W/m²K
Y_{ie} = 0.30 W/m²K

k_i = 47.3 kJ/m²K
k_e = 20.0 kJ/m²K

Retrofit: components analysis
TRANSPARENT



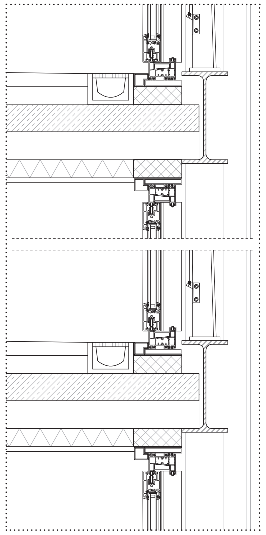
Layer	$g_{gl,n}$ [-]	$g_{gl+sh}/g_{gl,n}$ [-]	ξ [-]	Shutter	ΔR [m²K/W]
Triple pane (LE) + Aluminium frame	0.50	0.65	0.837	Plastics (with foam)	0.19

Layer	$g_{gl,n}$ [-]	$g_{gl+sh}/g_{gl,n}$ [-]	ξ [-]	Shutter	ΔR [m²K/W]
Triple pane (LE) + Aluminium frame	0.50	1	0.837	Plastics (with foam)	0.19

WINDOWS
U_{W+shut} = 0.82 W/m²K
U_w = 0.98 W/m²K

STOREFRONTS
U_{W+shut} = 0.82 W/m²K
U_w = 0.98 W/m²K

Retrofit: components analysis
WINTER GARDEN



Layer	$g_{gl,n}$ [-]	$g_{gl+sh}/g_{gl,n}$ [-]	ξ [-]	Shutter	ΔR [m²K/W]
Double pane (normal) + Aluminium frame	0.75	1	0.837	-	-

WINDOWS
U_w = 1.20 W/m²K

Layer	s [mm]	ρ [kg/m³]	M_S [kg/m²]	R_V [m²sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m²K/W]
INTERIOR							0,170
Finish/ Substrate	50	1500	75	0,0172	880	0,570	0,088
Insulation	50	32	1,6	0,0005	1030	0,034	1,471
EXTERIOR							0,040

FLOOR
U_w = 0.57 W/m²K

Layer	s [mm]	ρ [kg/m³]	M_S [kg/m²]	R_V [m²sPa/kg]	c [J/kgK]	λ [J/kgK]	R_i [m²K/W]
INTERIOR							0,100
Finish	12,5	900	11	0,0005	1090	0,210	0,060
Insulation	50	32	1,6	0,0005	1030	0,034	1,471
EXTERIOR							0,040

CEILING
U_w = 0.60 W/m²K

H_{ue} [W/K]	A [m²]	U [W/m²K]	Orientation	$b_{tr,x}$	Description
WINDOWS	93,8	1,20	E/W	1,0	Heat transfers between the winter garden and the exterior. One single orientation (E/W) and cavity (floor to ceiling) is considered. Sum of the transfers through: slinding glazed doors area, floor and ceiling.
FLOOR	35,2	0,57	-	1,0	
CEILING	35,2	0,60	-	1,0	

H_{iu} [W/K]	A [m²]	U [W/m²K]	Orientation	$b_{tr,x}$	Description
CW2	38,6	0,24	E/W	1,0	Heat transfers between the envelope components and the winter garden. One single orientation (E/W) and cavity (floor to ceiling) is considered.
CW3	17,1	0,21	E/W	1,0	
SL	15,5	0,25	E/W	1,0	
WINDOWS	31,6	0,97	E/W	1,0	

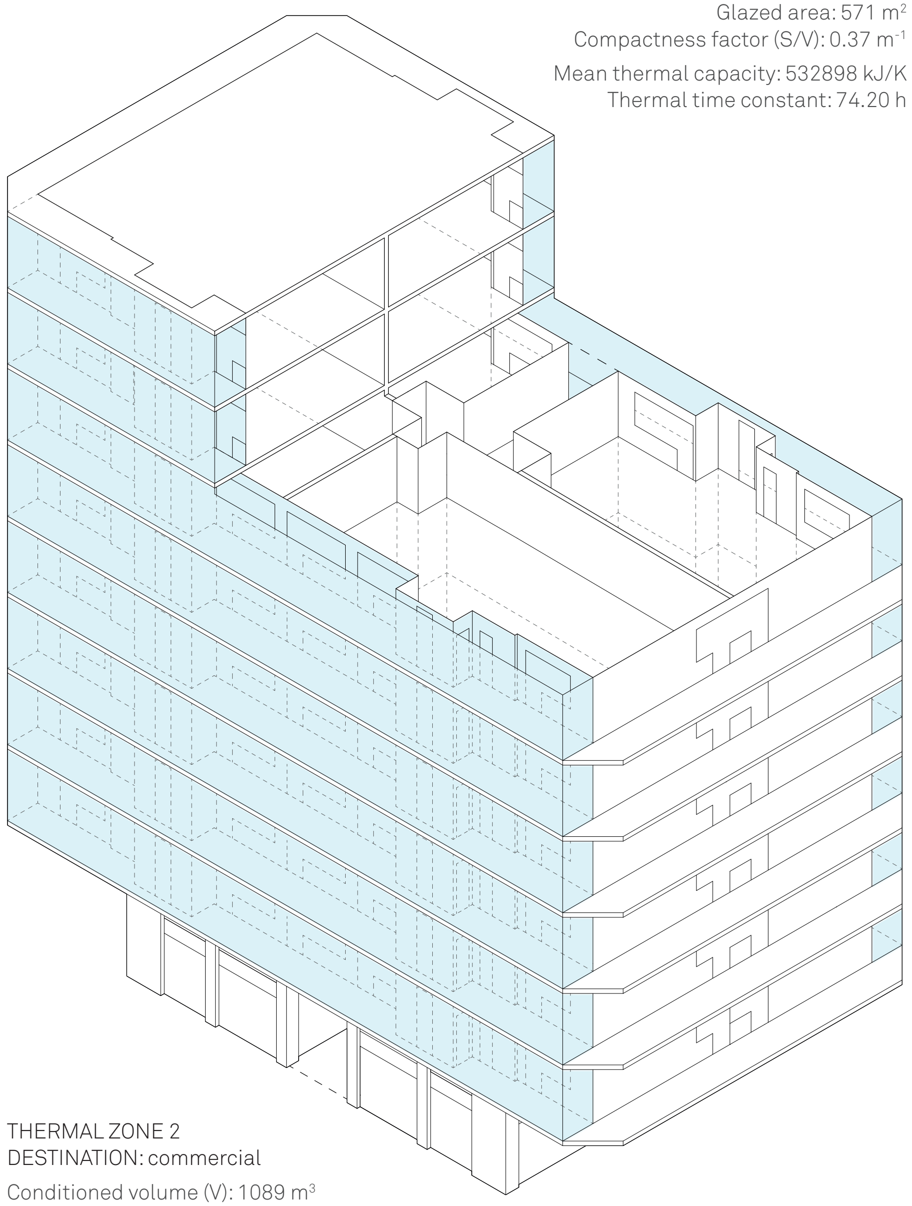
H_{ue} [W/K]	H_{iu} [W/K]	$b_{tr,x}$ [-]	
149,26	44,43	$b_{tr,x} = \frac{H_{ue}}{H_{ue} + H_{iu}}$	0.77

Building envelope
POST-RETROFIT BUILDING

THERMAL ZONE 2
DESTINATION: residential

Conditioned volume (V): 9639 m³
Conditioned net floor area: 2504 m²
Envelope area (S): 3550 m²
Glazed area: 571 m²
Compactness factor (S/V): 0.37 m⁻¹

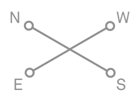
Mean thermal capacity: 532898 kJ/K
Thermal time constant: 74.20 h



THERMAL ZONE 2
DESTINATION: commercial

Conditioned volume (V): 1089 m³
Conditioned net floor area: 189 m²
Envelope area (S): 683 m²
Glazed area: 103 m²
Compactness factor (S/V): 0.63 m⁻¹

Mean thermal capacity: 37242 kJ/K
Thermal time constant: 27.04 h



TYPICAL FLOOR

Vertical opaque

Component: CW1
Area: 77.5 m²
Component: CW2
Area: 77.2 m²
Component: CW3
Area: 34.2 m²
Component: SL
Area: 31.0 m²

Vertical transparent

Windows
Area: 71.4 m²

Partitions

Single partition
Area: 61.2 m²
Double partition
Area: 25.6 m²

1st FLOOR

Horizontal opaque

Typical floor
Area: 139.5 m²

Partitions

Typical floor (B)
Area: 19.4 m²

9th FLOOR

Horizontal opaque

Roof
Area: 368.5 m²

GROUND FLOOR

Vertical opaque

Component: CW4
Area: 215.8 m²

Vertical transparent

Windows
Area: 56.3 m²
Storefronts
Area: 46.9 m²

Partitions

Ground floor
Area: 214.8 m²
Staircase
Area: 52.7 m²
Double partition
Area: 91.6 m²
Typical floor (A)
Area: 19.4 m²

Retrofit: heat transfer
THERMAL ZONE 1

VERTICAL OPAQUE	A [m²]	U [W/m²K]	Orientation	$b_{tr,x}$	$F_{sh,ob,dif}$ [-]	$a_{sol,c}$ [-]	ξ [-]
CW4	47,6	0,24	S	1,0	0,34	0,60	0,90
CW4	47,6	0,24	N	1,0	0,25	0,60	0,90
CW4	72,4	0,24	E	1,0	0,30	0,60	0,90
CW4	47,9	0,24	W	1,0	0,30	0,60	0,90
HORIZONTAL OPAQUE	**A [m²]**	**U [W/m²K]**	**Orientation**	**$b_{tr,x}$**	**$F_{sh,ob,dif}$ [-]**	**$a_{sol,c}$ [-]**	**ξ [-]**
GROUND FLOOR	214,8	0,45	-	0,5	-	-	-
PARTITIONS	**A [m²]**	**U [W/m²K]**	**Orientation**	**$b_{tr,x}$**	**$F_{sh,ob,dif}$ [-]**	**$a_{sol,c}$ [-]**	**ξ [-]**
STAIRCASE	52,7	0,73	-	0,6	-	-	-
DOUBLE PARTITION	91,6	0,62	-	0,6	-	-	-
TYPICAL FLOOR (A)	5,0	1,46	-	0,6	-	-	-

TRANSPARENT	A [m²]	U_W	U_{W+SH}	Orientation	$b_{tr,x}$	$F_{sh,ob,dif}$ [-]	F_F [-]	$g_{gl,n}$ [-]	g_{gl+sh} [-]	ξ [-]
B	15,56	0,98	0,82	E/W	1,0	0,30	0,28	0,50	0,47	0,837
C	11,42	0,98	0,82	E/W	1,0	0,30	0,28	0,50	0,47	0,837
D	9,95	0,98	0,82	S	1,0	0,34	0,27	0,50	0,42	0,837
D	9,95	0,98	0,82	N	1,0	0,25	0,27	0,50	0,44	0,837
E	17,72	0,98	0,82	E/W	1,0	0,30	0,17	0,50	0,47	0,837
E	14,20	0,98	0,82	S	1,0	0,34	0,14	0,50	0,42	0,837
E	14,20	0,98	0,82	N	1,0	0,25	0,14	0,50	0,44	0,837
F	3,14	0,98	0,82	E/W	1,0	0,30	0,22	0,50	0,47	0,837
G	7,09	0,98	0,82	E/W	1,0	0,30	0,15	0,50	0,47	0,837

THERMAL BRIDGE	L [m]	ψ [W/mK]	Orientation	$b_{tr,x}$	Description
C1	40,6	0,46	-	1,00	Balcony
C1	10,1	-0,60	-	0,60	Corner (concave)
C5	10,1	0,24	-	1,00	Corner (convex)
GF1	62,2	0,16	-	1,00	Connection to ground
IF3	28,5	0,49	-	0,60	Interstorey floor
W1	183,7	0,59	-	1,00	Windows

Performance index of the building envelope
SUMMER EQUIVALENT SOLAR AREA ($A_{sol,est}/A_{sup,ut}$)

THERMAL ZONE 1		THERMAL ZONE 2	
COMPONENT	$A_{sol,es}$ [m²]	COMPONENT	$A_{sol,es}$ [m²]
B	2,01	A	3,97
C	1,48	A	-
D	1,58	B	8,13
D	-	B	8,85
E	2,64	C	27,99
E	2,67	D	1,95
E	-	D	-
F	0,44	D	6,37
G	1,08	E	9,72
$A_{sol,est}$ [m²]	**11,89**	$A_{sol,est}$ [m²]	**66,98**

POST-RETROFIT

$A_{sol,est}$ = 78.87 m²

$A_{sup,ut}$ = 2243 m²

$A_{sol,est}/A_{sup,ut}$ = 0.035

Retrofit: heat transfer
THERMAL ZONE 2

VERTICAL OPAQUE	A [m²]	U [W/m²K]	Orientation	$b_{tr,x}$	$F_{sh,ob,dif}$ [-]	$a_{sol,c}$ [-]	ξ [-]
CW1	309,9	0,24	S	1,0	0,52	0,90	0,90
CW1	309,9	0,24	N	1,0	0,67	0,90	0,90
CW2	58,4	0,24	S	0,8	0,52	0,90	0,90
CW2	58,4	0,24	N	0,8	0,67	0,90	0,90
CW2	500,6	0,24	E/W	0,8	0,83	0,90	0,90
CW3	124,0	0,21	E	0,8	0,83	0,30	0,90
CW3	149,3	0,21	W	0,8	0,56	0,30	0,90
SL	28,5	0,25	S	0,8	0,37	0,30	0,90
SL	28,5	0,25	N	0,8	0,48	0,30	0,90
SL	190,9	0,25	E/W	0,8	0,66	0,30	0,90
HORIZONTAL OPAQUE	**A [m²]**	**U [W/m²K]**	**Orientation**	**$b_{tr,x}$**	**$F_{sh,ob,dif}$ [-]**	**$a_{sol,c}$ [-]**	**ξ [-]**
ROOF	368,5	0,21	-	0,8	-	-	-
TYPICAL FLOOR (EXT)	139,5	0,26	-	1,0	-	-	-
PARTITIONS	**A [m²]**	**U [W/m²K]**	**Orientation**	**$b_{tr,x}$**	**$F_{sh,ob,dif}$ [-]**	**$a_{sol,c}$ [-]**	**ξ [-]**
SINGLE PARTITION	489,2	0,71	-	0,6	-	-	-
DOUBLE PARTITION	204,8	0,62	-	0,6	-	-	-
TYPICAL FLOOR (B)	19,4	1,32	-	0,6	-	-	-

TRANSPARENT	A [m²]	U_W	U_{W+SH}	Orientation	$b_{tr,x}$	$F_{sh,ob,dif}$ [-]	F_F [-]	$g_{gl,n}$ [-]	g_{gl+sh} [-]	ξ [-]
A	52,08	0,97	0,82	S	1,0	0,37	0,46	0,50	0,27	0,837
A	52,08	0,97	0,82	N	1,0	0,48	0,46	0,50	0,29	0,837
B	62,08	0,97	0,82	E	0,8	0,60	0,46	0,50	0,31	0,837
B	62,08	0,97	0,82	W	0,8	0,60	0,46	0,50	0,31	0,837
C	192,80	0,97	0,82	E/W	0,8	0,60	0,45	0,50	0,31	0,837
D	21,28	0,97	0,82	S	0,8	0,34	0,35	0,50	0,27	0,837
D	21,28	0,97	0,82	N	0,8	0,44	0,35	0,50	0,29	0,837
D	42,56	0,97	0,82	E/W	0,8	0,60	0,35	0,50	0,31	0,837
E	64,64	0,97	0,82	E/W	0,8	0,83	0,43	0,50	0,31	0,837

THERMAL BRIDGE	L [m]	ψ [W/mK]	Orientation	$b_{tr,x}$	Description
C1	689,2	-0,07	-	0,91	Corner (concave)
C5	470,9	0,02	-	0,87	Corner (convex)
IF3	212,2	0,58	-	0,60	Interstorey floor
W1	1514,3	0,20	-	0,80	Windows

Performance index of the building envelope
GLOBAL AVERAGE HEAT TRANSFER COEFFICIENT (H'_T)

COMPONENT	THERMAL ZONE 1	THERMAL ZONE 2
	H [W/K]	H [W/K]
VERTICAL OPAQUE	51,7	354,7
HORIZONTAL OPAQUE	48,3	113,7
PARTITIONS	61,6	299,9
TRANSPARENT	91,2	407,6
THERMAL BRIDGES	67,2	281,1
$H_{tr,adj}$ [W/K]	**320,0**	**1457,0**

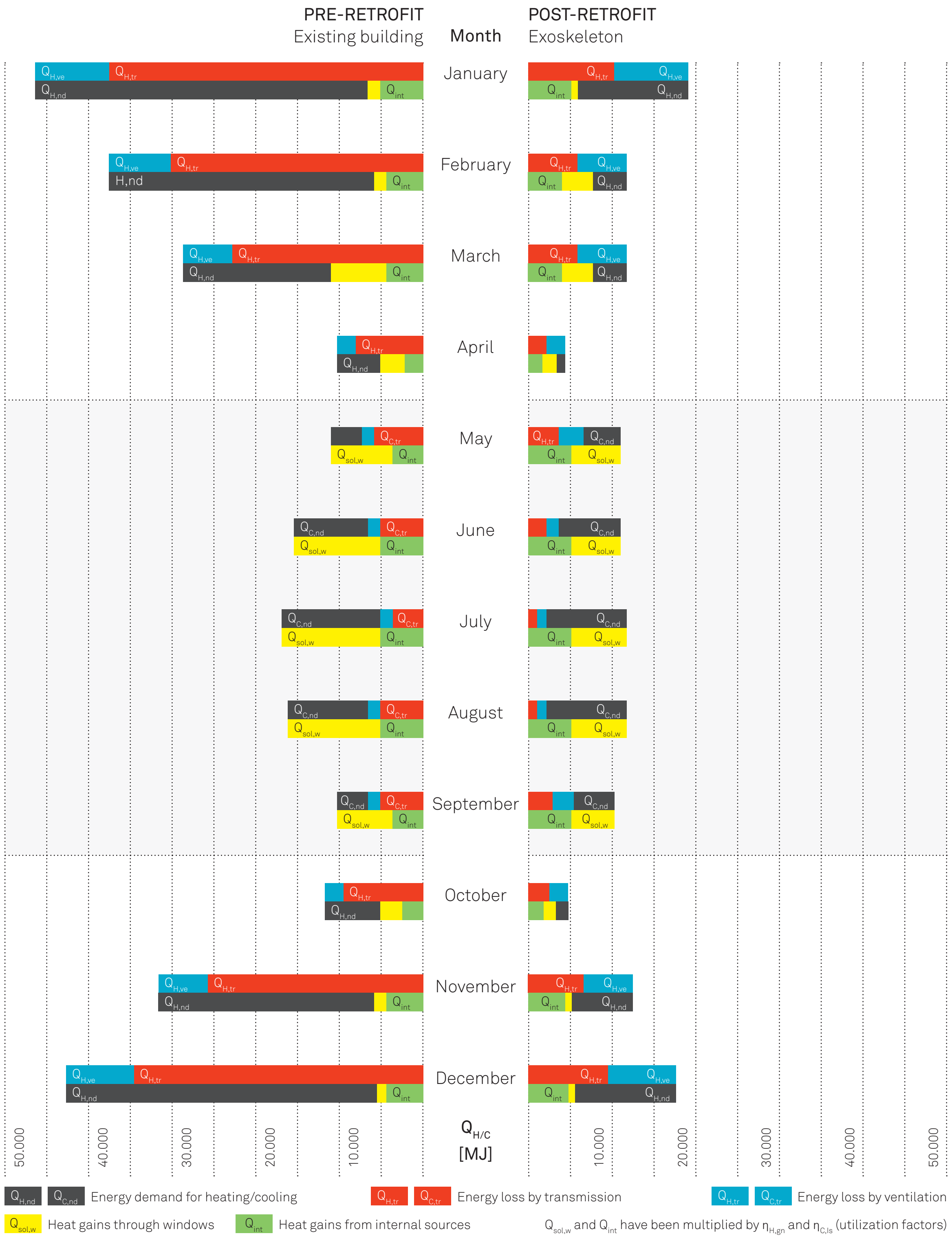
POST-RETROFIT

$H_{tr,adj}$ = 1777.0 W/K

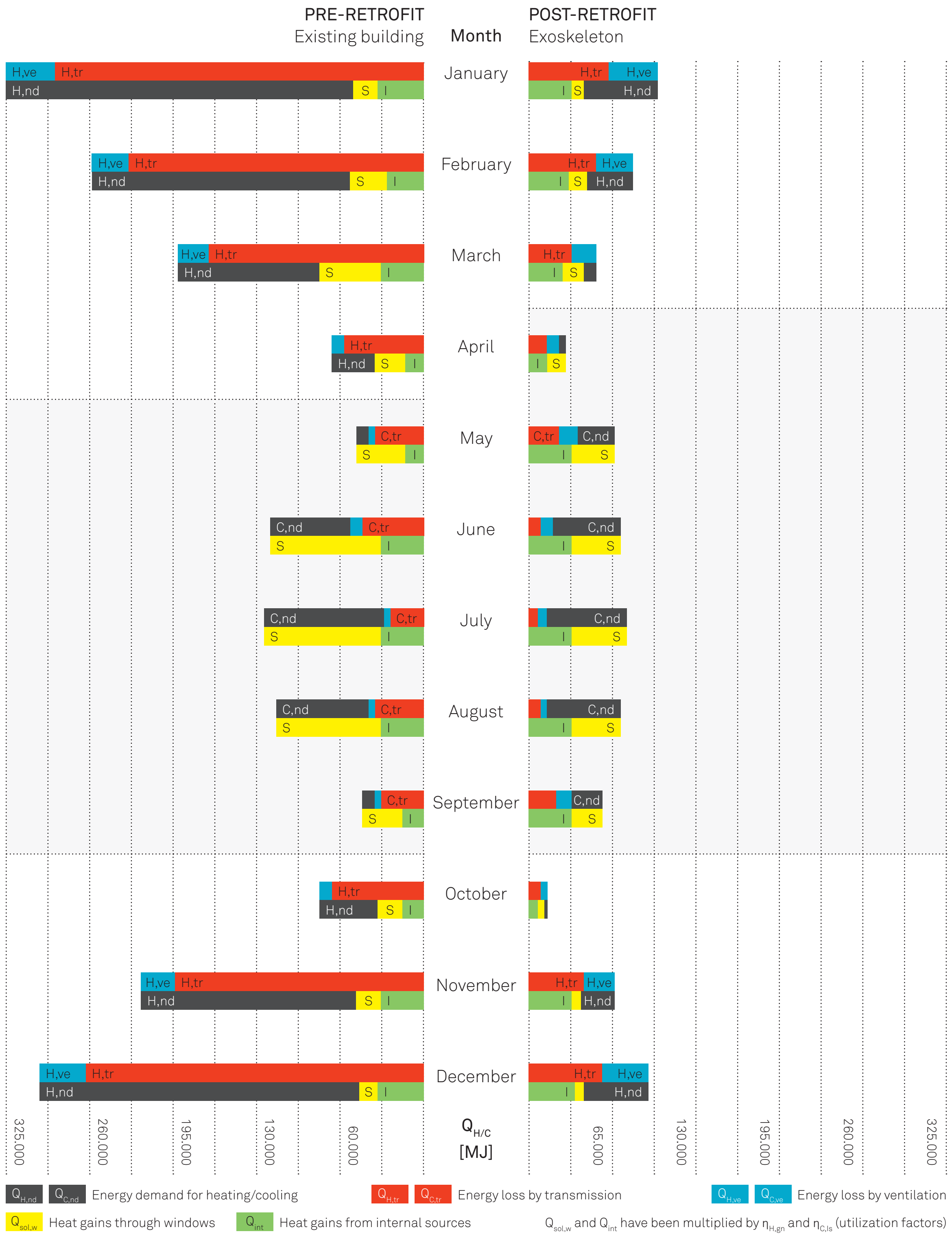
S = 4234 m²

H'_T = 0.42 W/m²K

Monthly energy balance
THERMAL ZONE 1



Monthly energy balance
THERMAL ZONE 2



Urban and district setting

The chosen residential case study, situated in Via Castelgomberto 35, is a 9 storey tall, mid rise tower building, located in the *Mirafiori Nord* district, part of the administrative unit *Circoscrizione 2* of the metropolitan area of Turin.

Although the district's name derives from the name of an ancient castle that stood since 1585 on the area now remarked as *Mirafiori Sud*, it will sound familiar to the most for the well-known presence of the FIAT *Mirafiori* industrial plant, erected since 1936 and onwards: a huge industrial complex, 3 millions square meters of built surface, to host no less than 22000 workers. Neighbourhoods and new towns, such as this INA-Casa district, were settled mostly around these vast industrial areas, although being not quite connected to the services and attractions of the city centre (reason why they had to be provided, in addition to the dwellings, with the basic services and essential commercial possibilities). However, the situation is now remarkably different: the INA-Casa neighbourhood has been gradually incorporated in the urban fabric. Even though its peripheral position, this district can be considered part of a consolidated and settled urban fabric: connected to the city centre and to other districts by public transportation, many commercial activities in the area and leisure possibilities, a prosperous street market in of via Baltimora.

The neighbourhood, however, maintained its original configuration: the five lots are clearly discernible from one another, as they form closed urban blocks, to which the access is only possible through mixed pedestrian/driveways access streets. Peculiar of these building blocks is the low density of construction, allowing for a great amount of daylight and natural ventilation through the well-distanced buildings (at least 25m far from one another). Furthermore, the original plan provided a generous quantity of green areas, which characterise until today this residential neighbourhood. These aspects confer to the INA-Casa residential towers and blocks a rather intriguing potential for regeneration: the qualities of this city's fragment, although functionally and architecturally obsolete, must be seen as latent future possibilities. The estate database for this district show that the value of refurbished dwellings is, whether in average, high or low end segments, almost twice as big as those of used ones. The objective of this design proposal is to asses the actual weaknesses of the case study (in respect to seismic vulnerability and energy performance) and to propose an integrate design solution able to make up these deficiencies, ultimately ensuring contemporary values and new life to this buildings and district.

Urban setting
MIRAFIORI NORD

Urban setting
VIA CASTELGOMBERTO 35

District

Inhabitants: 103258

Area: 3,762 km^2

Density: 27447,63 inh/km^2

Estate values
(OICT, 2018)

	Used	Refurbished
Max	2100 €/m^2	4281 €/m^2
Mean	1686 €/m^2	2922 €/m^2
Min	1114 €/m^2	2253 €/m^2

Project location

45° 2'54.95"N
7°37'56.30"E

Building data

Footprint: 368.5 m^2
Floor space: 2693 m^2
Volume: 9639 m^3

Ownership

Dwellings: 32
Commercial activities: 2

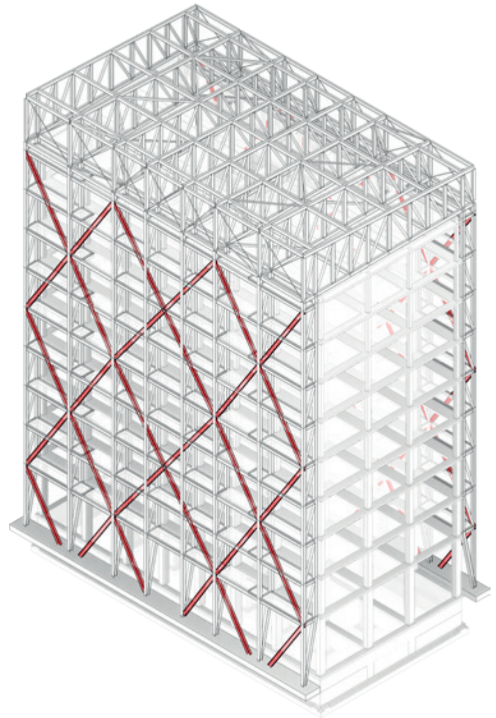
Structural prototyping

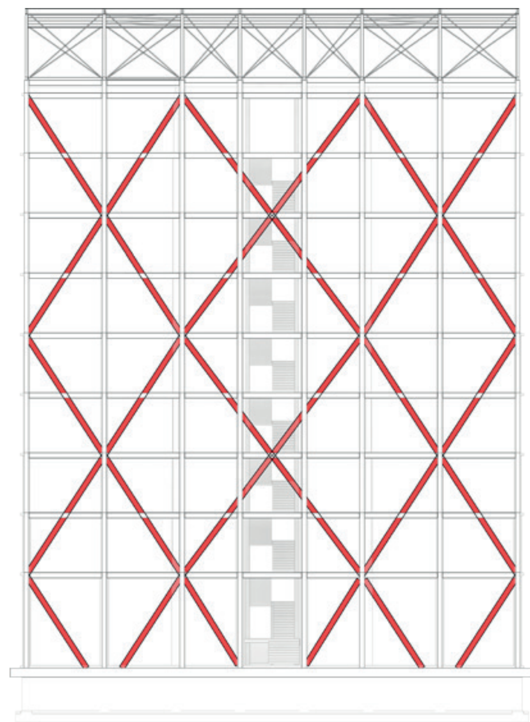
The first stage of our methodology has been the prototyping of a set of design options for the adaptive exoskeleton external structure. Our objective was to find the best solution, not only according to considerations about structural performance, functionality and architectural quality of the proposal, but also about its economic and technical feasibility. Also, a crucial point to us was the assessment of the environmental impact of the different solutions: based on experience driven considerations, the choice fell on the solution that would guarantee the best results and functionalities, at the minimum cost in terms of materials and resources. Three options have been proposed, each presenting different architectural, structural and functional features and perspectives of development. Most of the design choices that led to the definition of these three proposals are directly connected to the careful study of the building actual state and structural configuration. The regularity in plan and symmetry are remarkable features of this building, and its isolation and relatively high distance from other solutions allow for a great degree of freedom in the design of the exoskeleton structural system. However, the subtle differences between the distances of the plan's layout grids, the presence of a higher and less reinforced ground floor at the bottom and of enclosed overhangs on the long side of this building (overlapping the otherwise clear structural grid) led us to most of our design choices.

The first options makes use of portals crosswise the building. These portals, aligned with the original structural grid (exception made for the columns corresponding the overhangs, adjusted in order to avoid it), are than connected lengthwise with cross braces, which should guarantee the required stiffness also on this axis. This solution is thought to enhance to a maximum the influence of the exoskeleton in the short direction, where the building is indeed more vulnerable. However, this requires also diagonal braces crosswise, which can be an undesired limitation to the use of the exoskeleton's external plan. In addition, a higher amount of material is needed on top of the building to make the structure work as a portal: this might result in interesting possibilities, such as the addition of new storeys.

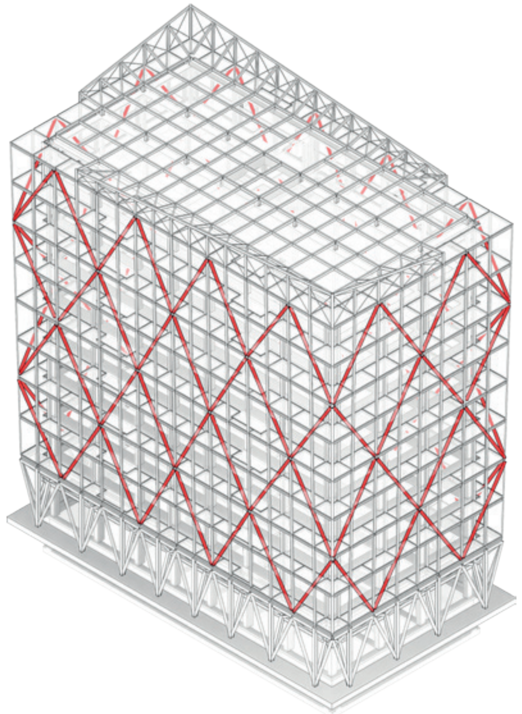
The second solution involved a radically different approach: the building is wrapped on each side by the exoskeleton. The new external beams are thought to act as a spradel beam, which allows the exoskeleton's outer grid to be completely aligned with the original structural grid. The new external floor slabs will act as a diaphragm between the interior structure and the external braced wall. The external configuration of braces is the result of the of a pseudo-diagrid conception, in which both vertical and diagonal members contribute both to carry the static and dynamic loads: the division of the original grid reduces the difference between braces' angles. The absence of braces improves the flexibility in plan in its usage; however, the high number of bars and connection make this solution extremely complex in terms of design and construction.

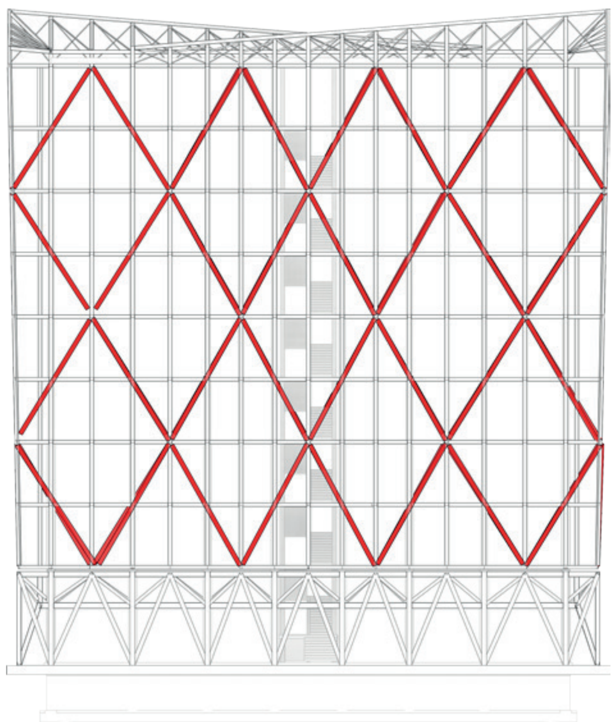
Structural prototyping
DESIGN OPTION 1





Structural prototyping
DESIGN OPTION 2





Final design development

Our choice fell on the third proposal, developed as an attempt to merge the qualities and perks of the previous options, it blends the second approach (wrapping up the existing construction) with some aspects of the first (structural subdivision, solution according to the overhang and diagonals geometry. A problem that we faced, in particular in the early stage of design, was connected to the odd number of spans (7 on the long side and 3 crosswise), which makes it impossible to achieve a diagonal geometry that would avoid at least some nodes between diagonals to occur in the middle of one of these spans. Lengthwise, we decided to accept this drawback: the east and west facade, in fact, adopt a pseudo-diagrid structural scheme, two storeys high. This approach eventually allowed to maintain free the middle span at the ground floor, aspect of particular interest because it coincides with the main entrances to the residential facilities. On the north ans south ends, on the other hand, we opted for a new solution: two vertical trusses, with k-shaped braces, span all over the building's height and stand out from the exoskeleton's outer layer. This choice allowed to achieve the same result also along these elevations, a solution that is thought to facilitate the entrance to the commercial spaces at the ground floor, while at the same time improving the exoskeleton's flexibility in the upper storeys, that could be eventually enhanced with additional balconies (a strategy that might result particularly useful on the south elevation, allowing for additional shading and well exposed external terraces) or, with a view to a more consistent redesign of the building's interiors, to additional vertical distribution shafts. Finally, the four sides of the steel frame are connected on top to a steel lattice, which absolves multiple functions: it rigidly links the higher ends of the exoskeleton and to the existing building, but also, being distanced from the original roof slab, it allows to host new function (such as green roof and common spaces) without causing additional stress the aged reinforced concrete slabs, rather completely relieving them from any additional load (i.e. live loads).

The advantage of the exoskeleton is that it enables an integrate design approach, in order to address the weaknesses and obsolescence of existing constructions. For this purpose, connected to each option we devised, yet in the initial stage, an architectural strategy that would further implement the results of the seismic retrofitting. We focused, finally, on the capability of external, additive technologies to renovate completely the passive physical behaviour of the building, and in particular of the building envelope. In particular, two strategies (the sun spaces on the east and west facade and the green roof on top) are both meant to enhance the performance of the building envelope, while also providing new features to the aged dwellings, in order to improve their flexibility and comfort. All of these aspects are thought to enhance the liveability and marketability of these apartments, eventually providing a regeneration of the whole neighbourhood.

Structural prototyping
DESIGN OPTION 3

Structural scheme

Pseudo-Diagrid + K- Braces

Number of bars

Beams: 747
Columns: 484
Braces: 250

Materials: volume

Steel (frame): 24,51 m^3

RC (foundations): 614,86 m^3

Materials: weight

Steel (frame + connections + coating): 192.447 kg

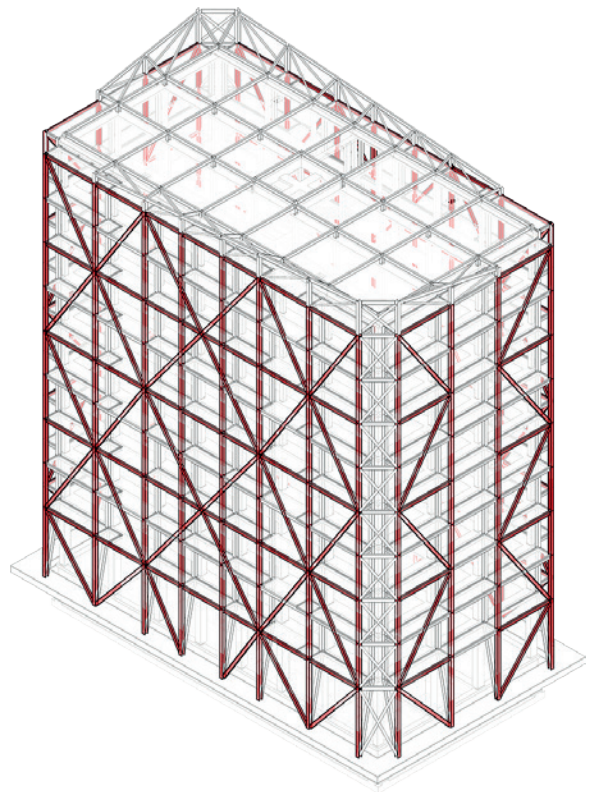
RC (foundations): 356.238 kg

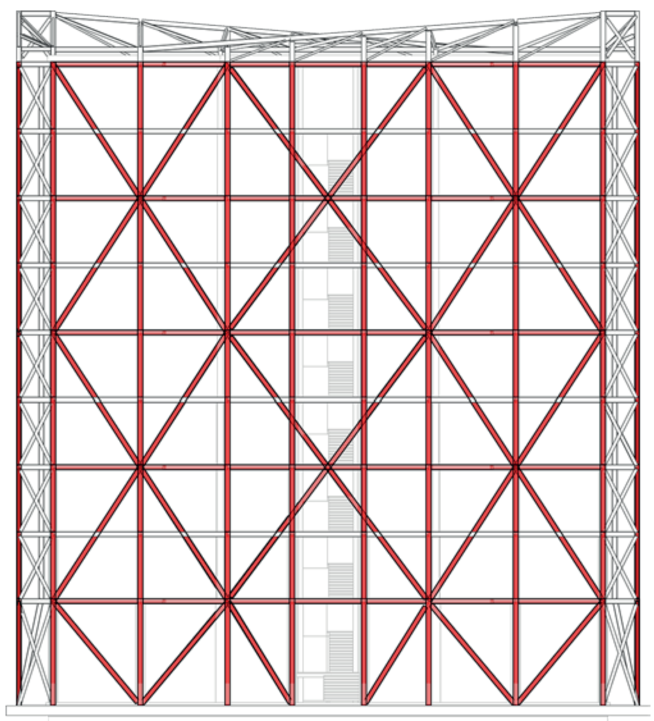
Perks

- Optimised steel usage
- Simple and regular layout
- Relatively easy construction
- Absence of braces crosswise
- Flexibility in plan
- Free spans at the ground floor and on north/sides

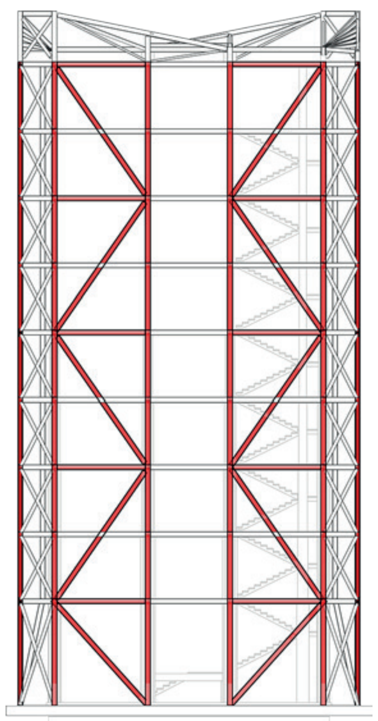
Cons

- Nodes in the middle of beams' span (eventuality of additional local stiffeners)
- Minor stiffness crosswise (weaker direction)
- Diagonals with different angles
- Slightly misaligned in respect to the original grid



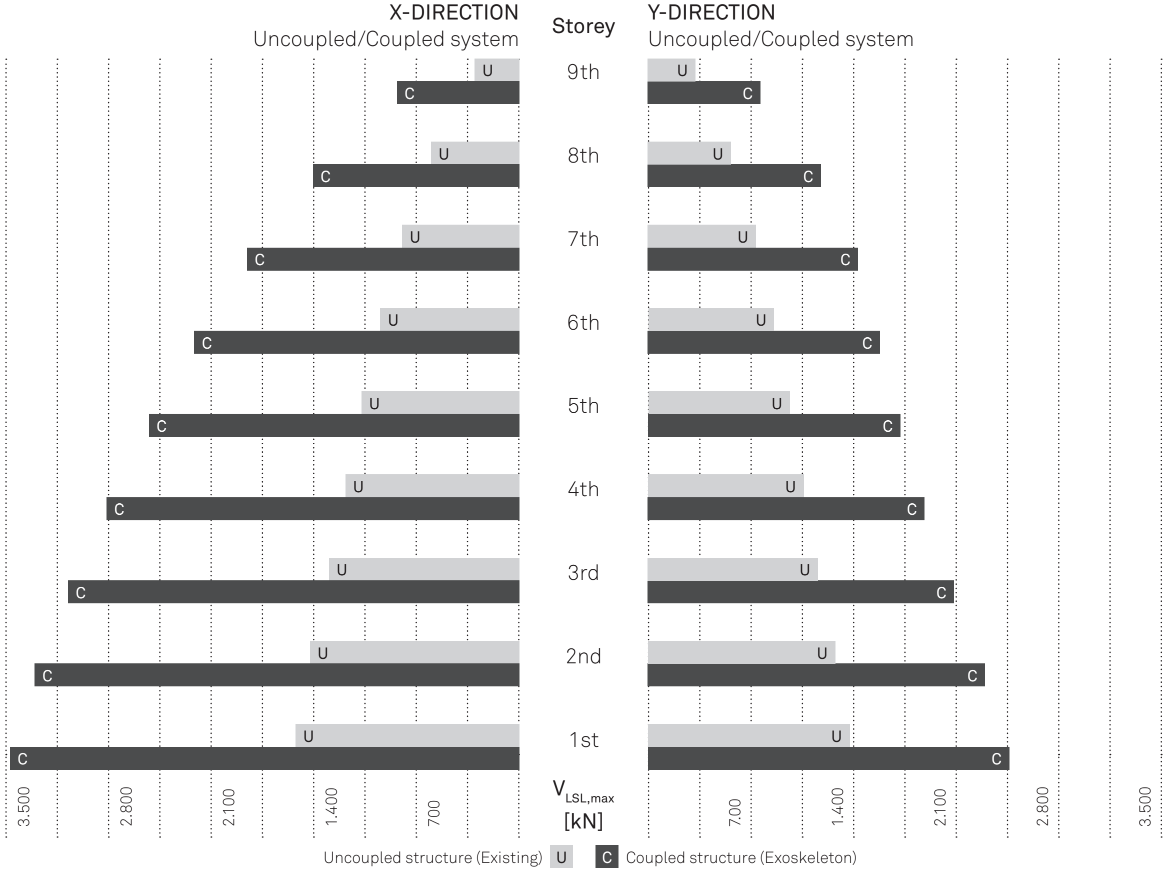


Pseudo-diagrid scheme

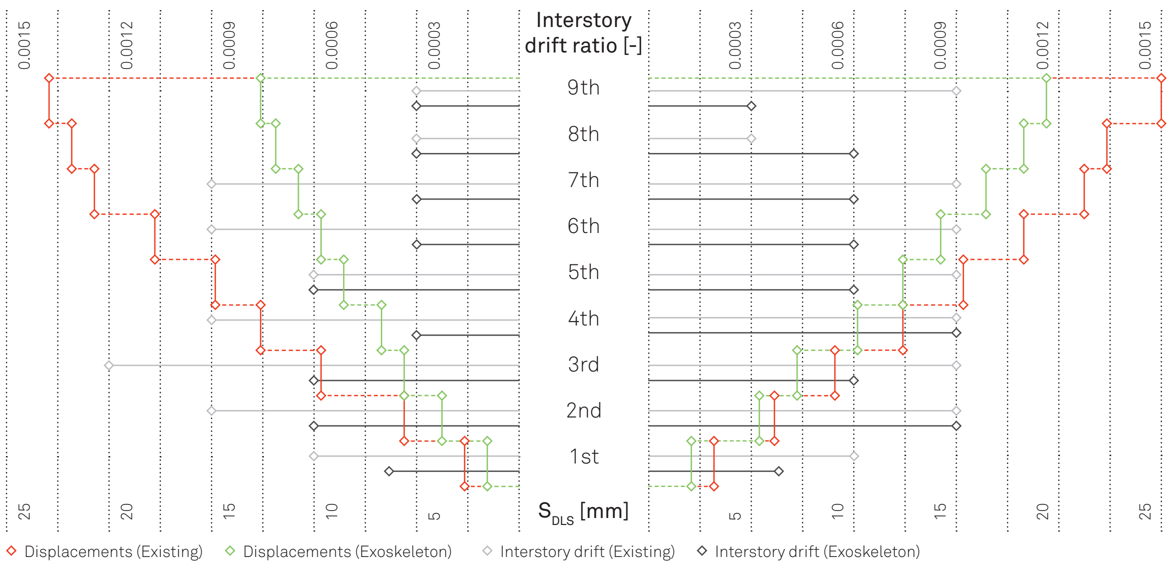


K-Braces scheme

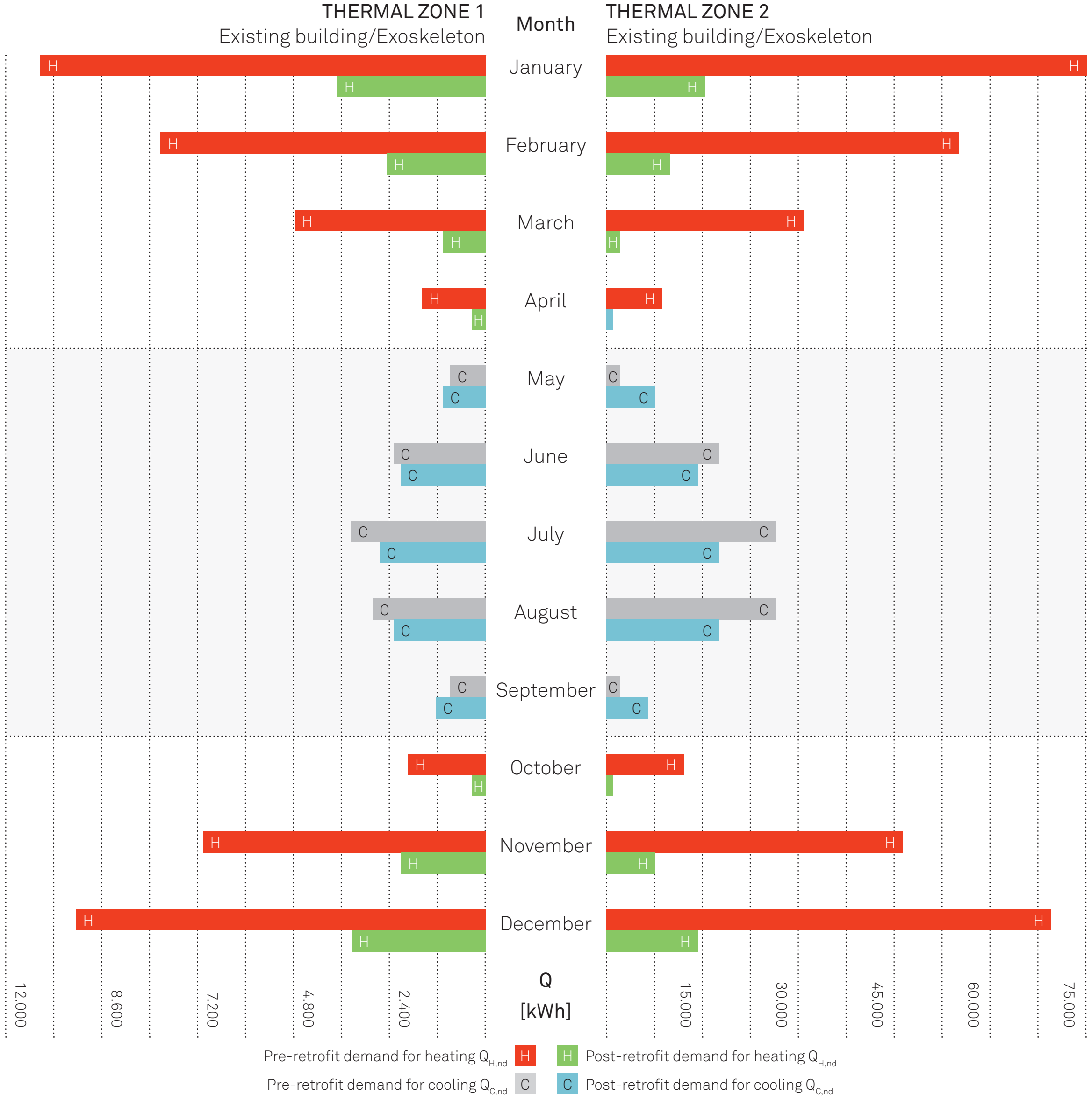
Seismic retrofit: results
SHEAR FORCES (LSL)



Seismic retrofit: results
DISPLACEMENTS (DLS) AND INTERSTORY DRIFTS



Energy retrofit: results
ENERGY DEMAND FOR HEATING AND COOLING



Energy retrofit: results
ENVELOPE PERFORMANCE

	PRE RETROFIT	POST RETROFIT	MAJOR RENOVATION 1st level
H'_T [W/m²K]	1,76	0,42	0,55
$A_{sol,est}$ / $A_{sup,ut}$ [-]	0,088	0,035	0,030

Energy retrofit: results
ENERGY EFFICIENCY

	PRE RETROFIT	POST RETROFIT	REFERERENCE BUILDING
$EP_{H,nd}$ [kWh/m²yr]	127,3	27,3	28.5
$EP_{C,nd}$ [kWh/m²yr]	28,8	23,9	23.9

Conclusions and further perspectives

Aim of this thesis was to explore the technical possibilities and boundaries of the regeneration of existing constructions, in particular of outdated and vulnerable constructions. The premises of the Adaptive Exoskeleton methodological approach, as a prototypical technology oriented at adapting old buildings to new standards, with an integrate and whole building approach, gain even more relevance when considered within to the whole of policies and economic conditions that, at present times, shape the construction industry and market. In other words, the cultural context and vision about the regeneration of the existing heritage are allegedly connected, and with ever growing urgency, to the technical and quality side of the built environment, which can not be neglected anymore: the challenge of retrofit. There is a growing need for assessing the possibilities of similar approaches, in relation to the expectations about economic and environmental sustainability, safety and sustainability. This thesis, and the speculative design proposal, addresses in first place these latter issues.

The development of the structural prototypes has been carried out in collaboration with a master degree student in Civil Engineering, the starting point was the consideration of the environmental impact of our design choices. His work dealt with the definition of a methodology for applying the *Life Cycle Assessment* process (generally applied to other industrial fields) also to the construction industry, and in relation to the retrofit of this case study. His results showed that this innovative approach allows for a dramatic reduction of the environmental impact of the entire process, when compared to the eventuality of a complete demolition and reconstruction. Naturally, the premise to this process was the ability of our project to achieve up to date safety and energy standards, all in all comparable to those in force for new constructions. Relying on the great relevance of the conclusions of his study, my work focused on this particular regard.

The conclusions of the structural analysis show a notable improvement in the performance of the building: displacements in service conditions have been drastically reduced, in comparison to the analysis of the existing building. Although we found that the actual degree of safety of the case study does not provide, also with respect to the current definition of seismic hazard provided by national and international design codes, particular preoccupations about its vulnerability, these considerations have been based on the assumption that the building lies in a rather high degree of conservation and compliance to the original design and construction process. However, it is not to exclude that the presence of defects invisible at bare eye, nor the occurrence of fast and unstoppable mechanisms of degradation of the building (a recurrent phenomenon of old reinforced concrete constructions), that would seriously endanger the structure of this residential building. Furthermore, the prototypical, experimental value of the Adaptive Exoskeleton methodology goes far beyond the contingency

of this case study, and might find applications in other, more vulnerable contexts. The achievement of experience in this field is, for me, a valuable accomplishment, since the devising and prototyping of solutions for broken, old construction is a radically experience based practice, in which the aspect of technical knowledge is crucial. The retrofit design lies, at present, in a preliminary stage, in which the structural system and behaviour and its relation to the architectural perspectives is clearly defined, leaving space, however, for a further process of optimisation.

In second instance, the evaluation of the energy performance of the building envelope gained a crucial relevant to this design: the results show that the exoskeleton, wrapping the existing building on each side, owes a great potential for whole life energy savings, by transforming this old, highly inefficient building into a contemporary *Nearly Zero Energy Building*. This conclusion is of great importance, in first place since it closely regards the issue of sustainability of buildings (and its crucial role in the transition towards sustainable societies and economies, as afore mentioned) and its relationship with that of their adaptation. In addition, the achievement of up to date standards of energy performance is an obligatory stage in order to improve the value and praise the latent architectural qualities of old dwellings. Also in respect to the process of design of the energy retrofit, the actual conclusions leave room for further improvements: in particular, the design has been concerned, for the most, on the achievement of a high performance in terms of reducing the amount of energy needed for space heating (accounting for the most part of energy demand of residential buildings). Further improvements might regard the provision of shading strategies, in order to reduce the demand of energy for cooling, and the implementation of a strategy for the introduction of sustainable energy sources (heat pumps and PV) and technical appliances (such as mechanical applications), achieving the reduction of the overall primary energy demand and enhanced comfort of the interior space.

Finally, on top of these technical considerations, another aspect should be thoroughly explored: the economic feasibility of the project. The premises of a light and fast construction process, able to transform existing buildings from without interfering with their serviceability, own a great potential. This potential, however, should be tested also within the context of the actual market and societal conditions: the contemporary policies about building policies, however, evolve promisingly in this direction. Yet, not only the financial aspect counts in terms of feasibility: the renovation practices might find a great ally in the conception of participative and collective methodologies, further improving the potential of buildings' regeneration. In conclusion, I wish to be able to experience, in my future professional life, these aspects and to eventually to elaborate in depth the many and intriguing considerations that this thesis and project disclosed to me.

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