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TECHNOLOGICAL AND FUNCTIONAL OPTIMIZATION OF A MODULAR CONSTRUCTION SYSTEM FOR FLEXIBLE AND ADAPTABLE MULTI-FAMILY HOUSING

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ABSTRACT

Nowadays one of the new challenges that must be faced in the megacities is certainly the guaranty of settlements and lodgings with good performances realized with a quick and off-site construction system due to the growth of world population, the rapid urbanization, the migration's intensification toward the rich countries and the new users requirements. The paper describes a study for an energy efficient, low cost construction modular system for multi-family housing, providing a high degree of flexibility and modularity. The first part of the research focuses on a state of art on housing projects realized in different countries. A critical review of these buildings leads to highlight the best technical and functional characteristics for each one with the aim to define a new proposal. The second part focuses on the identification of a modular grid allowing the creation of different flat layouts through the aggregation of modular units (rooms). The grid allows the addition of transitional spaces such as balconies, loggias and sunspaces according to the users' wishes. Facades are modular as well, allowing prefabrication of envelope units. Different structural systems were analyzed those most suited to the required flexibility. The main goal of the study is to

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overcome the rigidity typical of prefabricated solutions developed in the previous decades, providing a modular lightweight construction solution for housing. In conclusion the paper presents all the different options, the pros and cons for each of these and it proposes a final solution that is still under development in terms of energy, cost and constructability analyses.

Key words: social housing, low costs, modular construction system, flexibility, adaptability.

Introduction

One of the new challenges that must be faced in the megacities is certainly the guaranty of settlements and lodgings with good performances realized with a quick and off-site modular construction system adaptable to different social and climatic contexts, due to the rapid urbanization, the migration's intensification toward the rich countries and the new users requirements The research described in this paper starts from needs that today are not completely satisfied. On one side the houses users desire economic spaces and good architectural quality, with short time construction and low energy demand. On the other side the "construction world", that is not always able to effectively optimize the design and the construction hardly, guarantees high quality performance while keeping costs low (Boltri et al., 1995) [1] . A possible solution can be use prefabricated constructions. Industrialisation of the building process has long been considered a way to increase productivity and cut production costs while guaranteeing high performance standards (Sarja, 1998) [2]. Thanks to the new dry construction techniques, not only with concrete, but also with timber and steel, and also thanks to new industrial production of building components (Zambelli, 1981) [3], it is now possible overcome the deficiencies, monotony and lack of flexibility of the first post-war prefabrication techniques (Staib et al., 2008) [4]. The basic idea corresponds to an open system (Kendall, Teicher, 2000) [5], constitutes by a design systems, which allows flexible lightweight construction, with attitude to change. Adaptive systems, changeable and customizable both in external and internal finishes. It is also flexible in terms of performance: thermal comfort, noise, light, users privacy, etc.. The identification of a modular grid allowing the creation of different flat layouts, was an essential step to achieve this result.

Usually international researches on this topic focused often on the optimization of specific areas: architectural design, structural design, 3D panels, etc. The aim of the work was to optimize the supply chain for residential buildings (design and production) throughout modular construction systems adaptable to different conditions, studied considering the complexity of the construction system.

Methodology

The aim of this study is, as mentioned, to identify a complex system, which can integrate different flexibility variables: spaces and its quality, adaptability for future changes, construction time, cost and quality of the construction. The methodology, followed step by step for the research, is illustrated in Figure 1. The first part of the work, to achieve this goal, leads to identify a modular architectural grid based on the aggregation of modular units (rooms). The grid allows the addition of transitional spaces such as balconies, loggias and sunspaces according to the users' wishes. The critical review of various prefabricated building systems permits to achieve the goal from the early models up to the most current case studies. The critical analysis of these systems, also object of many interesting studies like (Gibb. A.; 2001 - Gibb. A.; Isack, F; 2003) [6], [7]. Important features in these systems are: weight, cost and flexibility. In addition, we carried out a survey on many housing projects in different countries, from many case studies collection books (Aurora Fernández Per, A; Mozas, J.; Arpa, J., 2009) [8], reviews, building manufacturers and construction companies reports and international researches. Two other points essential for the definition of the proposal were: first of all the relationship between the flexibility space and the quality perceived by the inhabitants, (Altaş, N.E.; Özsoy A., 1998) [9]; secondly the importance of the space adaptability correlated to the continuous evolving of the users requirements (Lans, W; Hofland, C.M., 2005) [10]. The second part of the work, starting from the architectural grid, is mainly a comparison of all the different possible structural solutions to find the best one for the new proposal. The following step consists in the selection of technological solutions for walls, floors and systems to obtain a new housing modular solutions. The final solution, which is still under study (Lucchini, A, et al.) [15] predicts the energy and environmental performances of an industrialised construction system developed together with a group of construction companies.

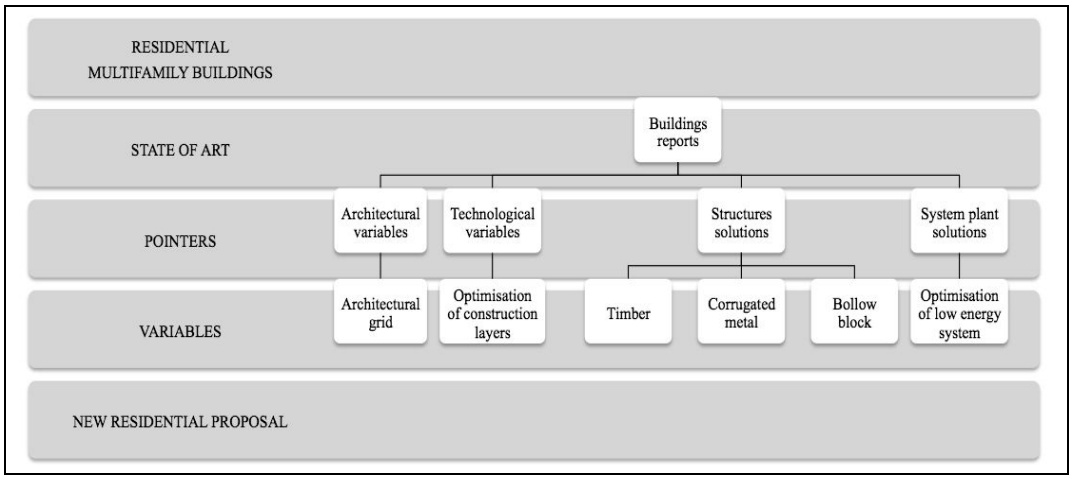

Figure 1: Methodology scheme.

Residential buildings overview

The first part of the research focuses on the study of many housing projects in different countries. This residential buildings overview leads to highlight the best technical and functional characteristics for each one in terms of architectural, technological and economical point of view, but above all those interactions. The aim of this state of art is, in fact, to put in a defined system a series of environmental, economic, technological and social factors that international researches have usually considered separately or partially (mostly qualitative type analyses). In the last decades in fact different analysis of the single aspects were conducted link to technology and energy, (like for example plan GREENBUILDING, or plans EULEB European High-quality low Energy Building, PEP Passive Promotion of European Houses, Passive PASSIVE-ON Marketable Homes for Winter and Summer Comfort and, on the depositor of the Housing, the plan SHARE Social Housing Action to Veteran Energy Consumption, all plans financed with measure IEE, Intelligent Energy Europe-Programme from the European Community), to sustainability (LCC-DATA Life-Cycle-Cost in the planning process) or to safety.

An overview of these researches highlighted a lack of studies on technological flexibility and performances that leads to operative suggestions; the works provided correct and innovative theoretical definitions and guidelines without practical recommendations or economic feasibility.

The first necessary step is to restart from the Housing term at the macroscale with a definition of new architectures, of new models of use, redefinition of the functional minimums but also at the microscale, with innovative ecological solutions. The objective, ambitious but necessary, is to realize high quality buildings with a controlled cost and time, to create a building innovation accessible for all. This means to act mainly on the productive process optimization and the construction management: design and process innovation in buildings. For better understanding the relationship costs / quality and performances / technical solutions, some recent residential experiences are analyzed punctually to identify the positive aspects that could become the main input for the definition and realization of energy efficient, low cost construction system for multi-family housing, with a high degree of flexibility and modularity.

Residential report as a tool building overview

The residential reports are organized in four sections that represent different levels of reading and deepening of the projects. The Figure 2 represents a residential report type, a sort of navigator to better understand how they are organized and they work.
In the first section there are the main data (masterplan, construction index, constructed volume, heated volume and, if declared, costs/m2) and the characterization pointers (keywords, strengths and weaknesses).

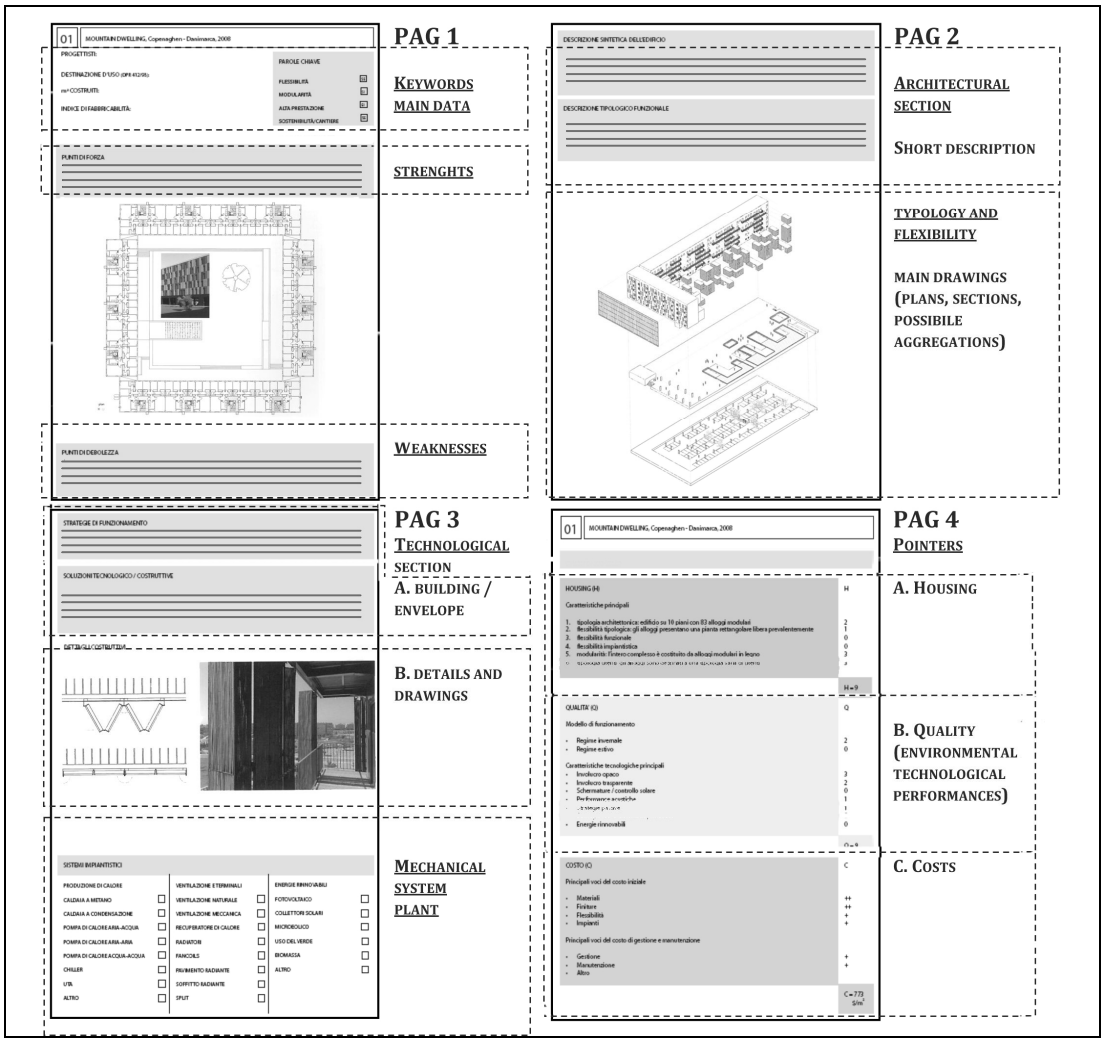

Figure 2: Residential report navigator.

The second section is the architectural one, which contains a short description of the project posing attention on some connoting aspects: basement, roof, balconies, loggias and greenhouses in relationship with the flexibility and their organization regarding the functions.

In the third section the technology is analyzed in three subtasks: building envelope, details and drawings and mechanical system plant. This section in particular contains constructive details in order to individuate the constructive phases and the techniques of assemblage adopted or the connections of materials/elements/components.

The fourth section is a sort of summary of the project in which all the information's are collected and analyzed with three pointers: housing, quality and costs. The

objective of this last part is not to assign a score to each project and then to have a chart, but to put in evidence the peculiarities and the relationship between architectural quality and costs, technological performances and costs. The elaboration of these reports became a very useful tool to individuate the main characteristic to design a low cost construction system for multi-family housing, providing a high degree of flexibility and modularity.

The next step of the research in fact foresees the analyses on different technical options chosen from the best variables individuates throughout the critical review of the reports.

The grid tool for flexibility solutions

The novelty of the new modular constructive system is the adaptability to different needs and requirements users that are continuously changing.
The variables complexity is significant and, as resulted, there are many options for the design of a new building. The society evolution and the new lifestyles lead to a revision and development of different flat typologies. There are interesting examples of housing that have tried to fulfill these new requirements. It is possible to identify, essentially, two types. There are buildings that contain the largest number of different apartments. There are, however, buildings that allow you to easily change the organization of the plan, encouraging adaptability of flats over time. The research is directed toward these buildings. The concept of "open building" summarizes a multi-disciplinary approach to the design, financing, construction and management of buildings allowing individual choices in a rationalised production and construction process (Kendall, Teicher, 2000) [5]. The analysis on these subjects permitted to identify some flats types in which the most important aspects are optimized: comfort, energy consumption, natural ventilation, adaptability, costs. The architectural grid is based on these flats integrated with the common elements, the horizontal and vertical connections, which allow to modify, over time, the spatial distribution of the flats in function of the new users requirements. The grid, in fact, permits to add transitional spaces such as balconies, loggias and sunspaces according to the users' wishes.

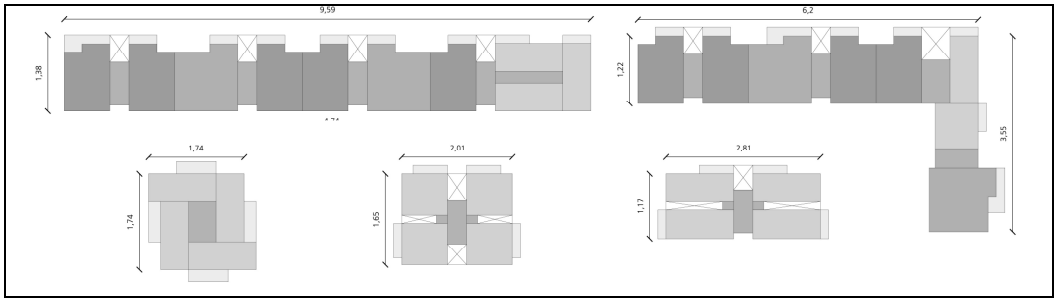

Figure 3: Possible aggregation scheme of the elementary functional flats units in a linear buildings (top) or in a tower (bottom)

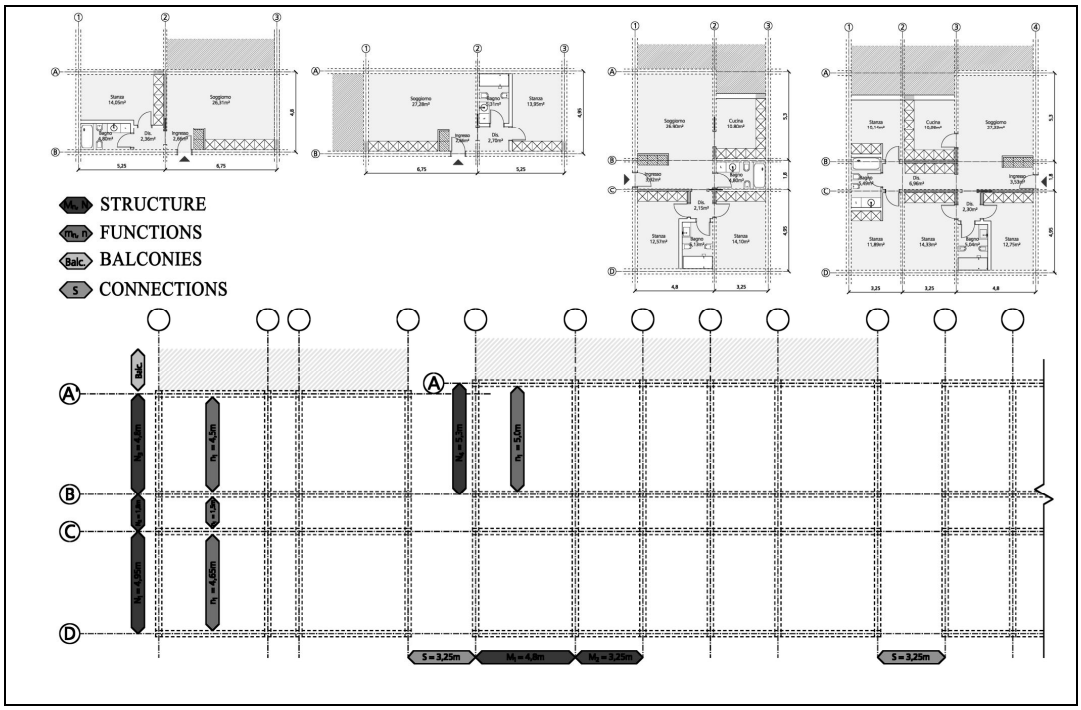

Figure 4: Example of same elementary flat units (top) and a part of the architectural grid (bottom)

Structural options

Given consideration explained below, flexibility and standardization are the main features to be achieved. From the flexibility point of view frame structural system was chosen. On the other hand, standardization leads to the utilization of prefabricated elements. For structural design of proposed system different materials were considered in order to evaluate the feasibility of each. Timber was considered as first option due to its several benefits in term of sustainability, strength, low weight and high prefabrication achievable. Then, a steel frame structure was analyzed as an alternative prefabricated solution. Finally, concrete cast-in-situ solution was taken into account as a comparison with Italian traditional construction technique. The structural preliminary evaluation of timber solution involved two different floor systems, timber joist (timber solution 1, Fig. 5a) floor and cross-laminated panel (timber solution 2, Fig. 5b). The former is a mono-directional floor commonly used in light timber frame systems; the latter was chosen as an alternative solution to reach a smaller section height (bi-directional floor). Among different advantages/disadvantages of different materials considered, evaluation of costs for each solution was defined as objective comparison parameter. This brought to values reported in table, which highlight that the cheapest option is cast-in-situ concrete, as expected. While cast-in-situ concrete has big disadvantages such as long construction

times, timber and steel are optimal solutions regarding construction costs. These solutions are capable of reducing significantly construction times. Finally, despite cast-in-situ concrete has proved the cheapest solution, timber was chosen as structural material for building system herein proposed, because is the solution that best fits with the overall objectives of this work. Its higher costs, calculating the full cost of the building, making it the best solution. For steel and cast-in-situ concrete frames the most commonly used floor systems were adopted (see Figure 6).

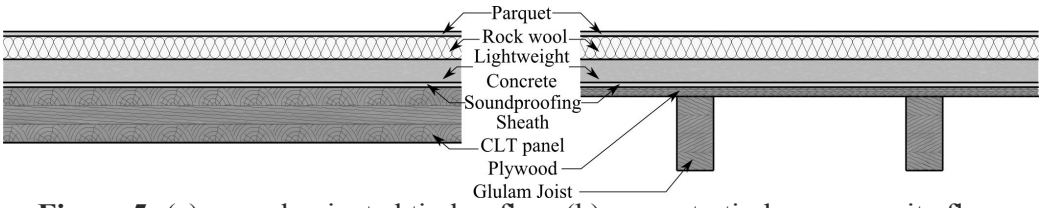

Figure 5: (a) cross-laminated timber floor (b) concrete-timber composite floor

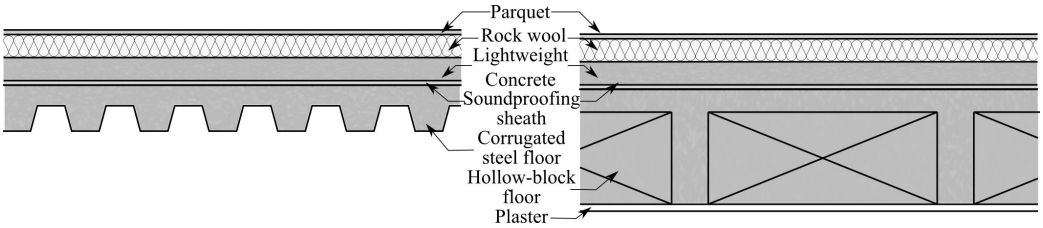

Figure 6: (a) corrugated metal floor (b) hollow block floor

Preliminary evaluation of structural members brought to element profiles summarized in Table 1.

Table 1: structural members preliminary design

	Struct. Element	b×h [mm]
Timber 1	Beam	120×440
	Column	150×150
Timber 2	Beam	120×400
	Column	150×150
Steel	Beams	160×160 (HE B 160)
	Column	100×100 (HE B 100)
Concrete	Beam	250×500
	Column	200×200

Table 2: Evaluation of costs

	Cost [€]	Cost [€/m²]
Timber 1	31,054	271
Timber 2	34,318	300
Steel	19,610	171
Concrete	13,479	117

Conclusions

The growth of world population, the rapid urbanization, the migration's intensification toward the rich countries and the new users requirements create new challenges that must be faced in the megacities like settlements and lodgings with high performances and quick and off-site construction system. The methodology carefully followed, the state of art on residential flexible solution actually on the

market and the architectural, technological and structural multitasking analyses of the research lead to the individuation of the main parameters involved in the definition of a residential buildings and above all the pro and cons for each one. The key for the definition of the best solution is the definition of the grid in function of residential modular system. With this scheme each designers have the freedom to develop a project the original. The novelty of this research was the integrated approach followed to define the best residential solution and in particular the architectural grid that could support designers to develop each project from the original scheme. Moreover the researches lead to the realization not only of a theoretical procedure, but the realization of a prototype, and finally a real project.

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