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ASSESSING THE DESIGN INNOVATION POTENTIAL OF TIMBER PREFABRICATED HOUSING THROUGH AXIOMATIC DESIGN

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ABSTRACT

Despite the current building sector slowdown in Italy, timber housing industry market is growing. But its growth has been limited mainly by the high costs of ad-hoc full-customized buildings and the lack of customer appreciation for mass-produced buildings. In order to satisfy the current demand for affordable customized housing, building industry should focus on solutions based on the combination of personalized and mass-produced parts. In this way, clients would have the chance to personalize crucial parts, and building industry can limit costs by the mass-production of the others. This combination between mass production and customization involves artefact flexibility and robustness with regard to the designer's viewpoint. These requirements are set in the conceptual design phase, but in this stage architect's decision making is not adequately supported. Since Axiomatic Design (AD) is able to support the analysis of designs with respect to the specified requirements, AD is applied to the review of prefabricated housing archetypes and current timber construction systems. This study shows the effectiveness of applying AD to prefabricated building design: crucial design decisions that affect the specified requirements are identified; inputs limiting their fulfilment in the timber building prefabrication are highlighted, and recommendations for developing adequate systems are provided.

INTRODUCTION

Although currently in Italy the building sector is in recession, timber housing industry market is increasing [1]. However its wide development has been limited mainly because of the high cost of ad hoc solutions on one hand, and the lack of customer appreciation of mass-produced solutions on the other hand. The approach based on ad-hoc full customized buildings allows a great deal of customization, but raises the cost. On the contrary the approach based on mass-

produced buildings assures lower costs, but impedes their customization and consequently the customer appreciation. In order to increase the timber prefabricated housing market, building industry should satisfy the current housing demand for customized buildings at affordable costs. According to mass customization, this aim is achievable by adaptive designs in which customized parts are combined to mass-produced parts [2]. In this manner, clients have the chance to personalize parts that are crucial for them, and building industry can limit costs by the mass-production of the others.

In the mass customization, artefact robustness and flexibility, both from the designer's point of view, are crucial requirements. These abilities depend greatly on decisions made by architects at the conceptual design phase. In this phase architects usually use experience and previous knowledge to formulate an early design concept, but this approach is nowadays often not adequate due to the current complexity [5]. AD has proven being able to support the analysis of design concepts with respect to the specified requirements [4, 3].

In this study, AD is applied to examine a selection of well-known modernist housing archetypes. These case studies are selected because of their link to prefabrication and their robustness and flexibility in order to guarantee attended performances and to satisfy different clients' preferences or the architects' creative freedom desire. Crucial design decisions that affect these requirements are identified by AD and validated through the comparison with the architect's choices documented by their writings. This analysis shows that artefact robustness and flexibility from the architect's viewpoint are fostered by the functional independence between the defined space and the chosen construction and by the functional independence of the respective sub-systems. The results prove firstly the ability of AD to support early architect's decision making for addressing design towards solutions better able to perform the specified requirements. Secondly crucial early

design decisions that affect these requirements are identified. Moreover the timber construction systems commonly applied by the Italian timber building industry are reviewed by AD. This investigation shows that these systems limit the abilities of design to be robust and flexible from the architect's viewpoint because of unwanted functional interferences between building parts. Accordingly recommendations for their review and improvement are suggested in order to define building systems better able to satisfy the current demand for customized houses at affordable costs.

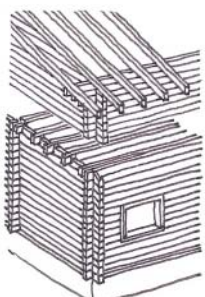
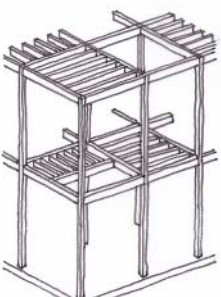
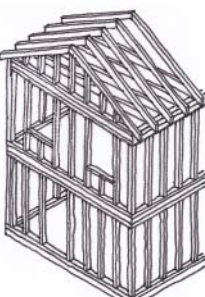
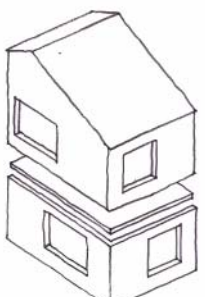
BACKGROUND

Italian Timber Building Industry

Despite the deep crisis of the Italian building sector, timber housing industry market is constantly growing [1] due to the high performances at relatively modest cost and the short time of construction that timber systems are able to guarantee. Statistical analyses show that between 2006 and 2010 the number of timber houses is quintuple (82% of single houses, 9% of two-family houses and the remainder of multi-family houses), and forecasts estimate a further grow of 50% in future [6]. Since in Italy the housing market is segmented due to the high heterogeneity of the housing demand [8], this situation entails the development of customized houses at affordable costs without prejudicing their performances in order to satisfy

the varied demand. Timber building industry shows to be able to provide low-cost mass-produced buildings on one hand and full customized buildings on other hands. The adoption of mass production procedures permits consistent economies, but the artefact is highly standardized, and the customer appreciation is low because of the strongly limited chance of customization. In alternative to low-cost mass-produced solutions, building industry proposes ad-hoc full-customized solutions. In this approach, building components are one-off designed according to specific client's needs and then factory made, but building costs are high. Due to the lack of variety of low-cost mass-produced buildings and the high costs of full-customized buildings, timber building industry is not able to satisfy the current housing demand. A different approach is needed.

Italian building industry has available different types of timber construction systems (Table 1) [7]: log construction, frame construction, platform frame construction and loading panel construction. Statistical analyzes highlight that timber building industry in 2010 has realized 44% of buildings by platform frame system, 33% by loading panel system and 14% by log system while frame system has been rarely used. Moreover forecasts expect an increasing use of the loading panel due to marketing strategies and customer appreciation. This approval is determined by similarities between this system and typical construction systems in Italy such as masonry [1].

 <p>Log construction</p> <p>It is an antique system used for mono-storey and two-storey buildings (especially single houses). It is a box-shaped construction similar to masonry. Walls are made by the overlapping and connection of timber trunks on the site. Then they are covered externally or internally with insulation while timber trunks are visible on the opposite side.</p>	 <p>Frame construction</p> <p>It is an antique system (significant ancient examples are available in Orient as well as in Europe). It allows up to 3-4 floors. It is a timber frame realized by square or rectangular timber section elements (beams and pillars). Elements are connected by wood-working or steel joints. Stiffening elements (panels or timber tie-beams or steel tie-rod) are placed vertically and horizontally in order to absorb horizontal loads and transfer them to the ground. Façades are usually realized by infill insulated panels that are fixed externally to the timber frame that remains visible inside the building.</p>
 <p>Platform frame construction</p> <p>It is usually very popular around the world for mono-storey and multi-storey buildings. It consists of storey-high pre-assembled frames of linear timber members that are braced by flat cladding panels or diagonal boards, filled with insulation material and covered on both sides with sheathings. Insulating material is placed between the members. The construction is based on the principle of stacking storeys one upon the other. The assembly on site involves erecting and jointing wall panels.</p>	 <p>Loading panel construction</p> <p>The recent (developed in the first half of the 90s) and growing system for mono-storey and multi-storey buildings. It is a box-shaped construction similarly to masonry. It is made by resistant and rigid panels manufactured in factory by crossed layers. Then on the building site, panels are connected and covered with insulation externally and plasterboard internally. Walls are usually one-floor high; therefore each floor is the platform for the following story.</p>

Tab. 1: Timber construction systems in use in Italy [7]

Building Prefabrication

Building prefabrication consists of linear, planar or spatial building elements that are pre-made in factory, and then assembled and installed permanently on the building site [9].

Before the development of information and digital technologies, building manufacturing processes were limited to mass production. Mass production consists in the creation of large amounts of identical parts in order to reducing costs significantly, but limiting individual choice. Thanks to the introduction of information and digital technologies and their advances, building industry is nowadays able to rapidly respond to individual customer's needs. This strategy, called customization, allows providing a unique product built according to specific customer's requirements, but costs are typically high [10]. Mass customization is a mix between mass production and customization, based on the combination of prefabricated mass-produced parts and customized parts. It allows providing personalized artefacts at affordable costs [2].

This study asserts that mass customization, especially adaptive customization, is a suitable approach for the improvement of the Italian timber building industry in order to satisfy the current housing demand. By this approach, prefabricated buildings result in being composed of customized and mass-produced parts. In this way, building industry is able to personalize parts that are decisive for clients and to limit costs by the mass-production of the others. In order to develop solutions that are better able to satisfy the current demand for affordable customized houses, artefact robustness and flexibility with respect to the architect's viewpoint appear crucial. In general artefact robustness from the designer's viewpoint is the ability of an artefact to produce the expected performances despite being subjected to uncertainties and disturbances (e.g. changing customers or functions or physical components) [3]. Artefact flexibility from the designer's viewpoint expresses the ability of an artefact to be adapted in terms of functionality and performance features in order to yield similar design families with little effort, time, or penalty in response to market demand. Flexibility is meaningful if the functionality of the artifact varies in some way in terms of set of functional requirements implemented by the artifact or in terms of specific artifact performance features [4]. According to Barrow et al., these abilities depend mainly on decisions made by architects at the conceptual design phase [11]. Unfortunately in this phase architect's decision making is not supported by suitable approaches. Usually a design concept is generated very early on the basis of a simplified problem statement defined by architects using previous experiences and knowledge. Due to the current complexity, this approach is nowadays often not adequate [5]. Since literature shows several similarities among product industry and building industry, methods and strategies that are effectively employed in product and manufacturing design to achieve expected outcomes may be successfully transferred and applied to building design in the building industry [12].

AXIOMATIC DESIGN

AD is a design theory developed in engineering by Nam P. Suh and applied to many different design fields included product and manufacturing design [13]. AD is intended to support early designer's decision making from synthesis to analysis of the idea, and to selection of the appropriate idea among plausible solutions [14, 15]. It proposes a rational structure, a systematic procedure and principles of synthesis and decision making for the development and evaluation of designs with respect to their robustness [3] and flexibility [4] from the designer and user's viewpoints. In AD, designers must decide what they want to achieve in terms of functions before considering how to achieve it in terms of physical components. Functions of an artifact, also called functional requirements (FRs), are what the artefact should perform to satisfy customer's needs [14]. They involve the exchange of signals, information, materials, forces, and energy [4]. Designers define the expected functions in terms of FRs. In addition they specify restrictions (called constraints - Cs) on the artifact and desirable qualities or attributes that the artifact should have or on how the artefact must be designed to be accepted [4]. FRs are then mapped into physical components, called design parameters (DPs) that implement physically the defined functions. In general, the mapping between FRs and DPs may be one-to-one, many-to-one, or one-to-many. In one-to-one mapping, each DP implements one FR while in many-to-one a DP implements many FRs [4]. In AD, the definition of FRs and the subsequent assignment of DPs are both dependent on the independence axiom. The independence axiom or axiom one states that the independence of the FRs as well as the one-to-one mapping between FRs and DPs must be maintained to minimize coupling between FR/FR and FR/DP pairs and avoid conflicts [14, 15]. Such decoupling warrants that a variation of one DP or one FR will not destabilize the whole solution. In this way, it is fostered the artefact robustness from the designer's viewpoint [3]. Couplings are identified by the check of the design matrix (DM); so they can be reduced or eliminated. The second axiom fosters the artefact robustness from the user (consumer or manufacturer)'s point of view [3]. It states that a decoupled design should also follow the principle of minimum information for the user. This means that the user should not have to adjust any design parameter in order to benefit from the functions of the system [3]. Axiom two will not be applied in this study. Finally all the DPs components are physically integrated into one entity, and interacting components are connected by interfaces. In AD, every DP should be combined without introducing unwanted couplings between FRs and DPs and between DPs [14, 15]. When each DP implements one FR and the interactions between DPs are decoupled, the artefact scheme is defined modular architecture. This scheme fosters the artefact flexibility from the architect and user's viewpoint [4]. In this way, the artefact results in being robust from the architect's viewpoint and flexible from the architect's and user's viewpoints.

Previous studies have shown the compatibility of AD to the architects' approach in the conceptual design phase and benefits of applying AD to building design [5]. Since AD has proven to be able to guide the analysis of designs with respect to their robustness and flexibility from the designer's viewpoint, this study analyses by AD the concept designs of a selection of case studies. They are well-known houses linked to prefabrication and designed for being robust and flexible with regard to the architect's viewpoint in order to guarantee attended performances despite variable client's needs and to satisfy the architects' creative freedom desire and different clients' needs. The aim is to identify crucial architectural masters' design decisions that affect these requirements. The identified strategies are validated through the comparison with the architects' choices documented by their writings and critics' materials. The analysis takes then in account the timber construction systems commonly proposed and used by the building industry. They are examined in order to verify restrictions placed by these systems on the artefact robustness and flexibility in the building industry. Finally the results are used to outline recommendations for addressing the development of timber building systems that are better able to satisfy the current housing demand.

CASE STUDIES ANALYSIS

In the first half of the twentieth century between the two World Wars, a decisive transformation of architecture occurred as the result of the international modernist movement. This movement proposed an innovative change in architectural design based on criteria of functionality and flexibility and connected to technological innovation and a new aesthetics [16]. Since each building had to achieve the maximum functionality according to the user needs, new industrially-produced materials and technologies such as reinforced concrete and steel were adopted. They allowed avoiding constraints placed by traditional construction systems that limited the freedom of designing and the achievement of the expected performances [17]. Gropius, one of the key figures in this process, explained the new principles of the modern architecture as follow: "The nature of an object is determined by what it does []. It must perfectly serve its purpose; in other words, it must fulfil its function practically, it must be cheap, durable and beautiful" [18]. A new aesthetics was founded on the principle "form follows function" [19]. This principle means that the shape of a building has to be primarily based upon its intended functions. Therefore building aesthetics was subjected to the building functionality [16]. This aesthetics determined simple and clear forms; unnecessary details were removed. Also the loadbearing structure contributed with facade and interior layout to the definition of the building appearance. The natural appearance of a material had to be seen rather than concealed or altered to represent something else. Starting from the modernist architecture, architects were involved on prefabrication determining a profitable union between architecture and industry. Architects invested time and

energy for the development of building industrialization because they saw by it the chance to offer high quality houses to all at affordable costs and in a short time [16]. In the development of the modern architecture and prefabrication, three figures played a crucial role: Walter Gropius, Mies van der Rohe and Charles-Edouard Jeanneret-Gris known as Le Corbusier [20]. They tried to understand if prefabrication could be a process for architecture to improve the built environment including housing and how the quality of both, design and production, could concurrently be enhanced by new and innovative approaches. In this way, solutions proposed by these architects represent answers to these questions [18], and are considered archetypes. This study intends to uncover the lessons shown from a selection of prefabricated architectural examples in order to employ them for reassessing the future of prefabricated architecture. It takes in account two famous houses - Villa Savoye and Farnsworth House - that represent concretely the mentioned principles and innovative approaches to design and production by prefabrication. Architectural history critics consider them as modernist architecture archetypes on one side and well-recognized prefabricated architecture attempts on the other side.

Case Study #1: Villa Savoye

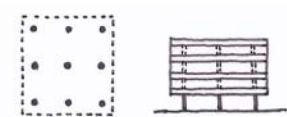

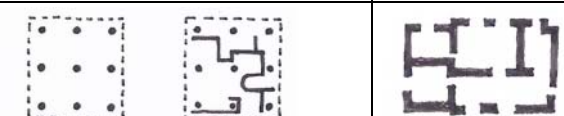
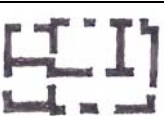
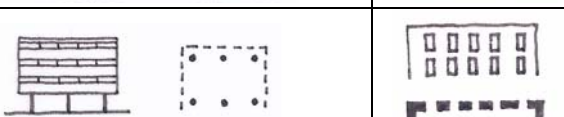
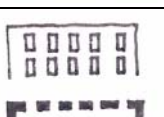
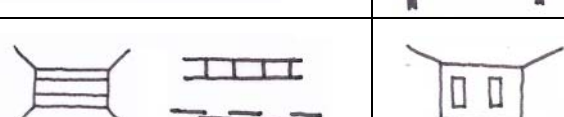

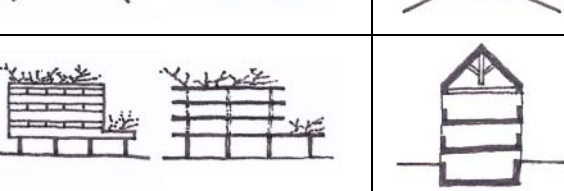

Villa Savoye was designed and built by Le Corbusier in 1929-1931 in Poissy (Paris) (Fig. 1).



Fig. 1: Villa Savoye

This weekend house represents concretely the aspects of robustness and flexibility from the architect's viewpoint combined to technological innovation and a new aesthetics theorized by Le Corbusier in a programmatic manifesto, "Toward a New Architecture". He summarized his innovative approach by five points shown in Table 2 and explained below: 1) *pilotis* – a reinforced concrete structural frame by pillars (called "pilotis") replaces the traditional supporting walls and lifts the building off the soil; 2) *free plan* – each floor plan becomes freely configurable (called "free plan") into rooms according to the user needs thanks to the use of pillars that replace supporting walls; 3) *free facade* – since facade does not carry out the supporting function, pillars are retreated from facade towards inside; interior partitions do not influence the facade design, and therefore facade can be freely configured (called "free facade"); 4) *elongated window* – since facade is totally independent with respect to the loadbearing structure

and thanks to the introduction of reinforced concrete facade, windows can be extended along the whole facade from corner to corner widening view and intensifying natural light entrance; 5) *roof garden* – thanks to the use of reinforced concrete and the introduction of a central heating system, the traditional inclined roof can be replaced by a flat roof allowing the realization of a terrace-garden on the roof [21].

1		
2		
3		
4		
5		

Tab. 2: Le Corbusier's five points (left) vs traditional solutions (right)

These results were fostered by an innovative and efficient use of the reinforced concrete in shape of frame [20]. In fact in that period, industry revealed some crucial capabilities of this material: once applied under the principle of achieving maximum results with minimum effort, reinforced concrete proved being capable of producing better structural results with less material bulk than any previously known material, with the exception of the steel frame [21]. The use of this new construction system allowed a creative freedom previously unimaginable for architects, and addressed architecture towards innovation and new production and construction methods based on rationalization, standardization and prefabrication [18].

Since AD provides criteria for the evaluation of designs regarding robustness and flexibility from the designer's viewpoint, AD is applied to the analysis of this case study. Design intents are expressed in terms of FR and related DP.

FR0 = provide a modern, isolated, comfortable, flexible and functional holiday house

DP0 = a pure-geometry, well-oriented, suspended and modular-architecture villa [23]

Architectural form is generally defined by architects and critics [22] as "the interplay of three converging vectors":

"topos" (relating to context, site and sun orientation), "typos" (relating to activities and space relationship) and "tectonic" (relating to construction for supporting and separating in order to create spaces). Site provides design inputs and constraints (Cs) on the definition of the solution or on how the solution must be designed to be accepted. Construction is generally distinguished among skeleton construction, massive construction and hybrid construction [23]. Skeleton construction is made from linear members, and thanks to this nature, it is able to provide shelter without conditioning the creation of interior space and without separating interior from exterior. On the contrary, massive construction is made from walls. Since walls perform both the loadbearing and enclosing functions, they create the interior space directly, and separate interior and exterior distinctly. Hybrid construction is a combination between skeleton construction and massive construction [23]. According to the architectural form concept previously defined, an initial minimum set of independent FRs that the artefact should perform is defined:

FR1 = accommodate clients' living pleasantly

FR2 = support client's living safely and comfortably

According to the Le Corbusier's approach, the artefact should be able to perform these functions optimally and freely without interferences between them in order to fulfill the architect's vision and to satisfy variable clients' needs. The architectural form has to be simple, primarily based upon its intended functions. An early architectural form is suggested (Fig. 2) that satisfies the expected requirements.

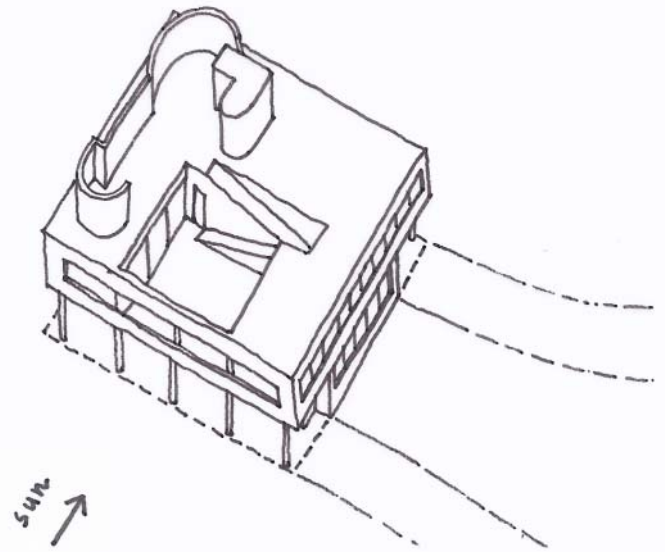


Fig. 2: Initial design concept – axonometric view

The proposed design is placed in the centre of a plot at the top of a hill, surrounded by high trees in the countryside of Poissy. The proposed dwelling is lifted off the ground to guarantee healthy life conditions and the best view of the natural surrounding while a garden on the roof provides to habitants the contact with nature. According to the Le Corbusier's statement, the ground is reserved for vegetation, car entering

and leaving while the dwelling is placed on the upper floors [24]. The design is optimized with respect to the sun orientation in order to maximize the availability of the sunshine inside the building [25]. This architectural form permits placing building on any terrain and sloping independently by the building's location, and there is no needed to restrict the garden area [21]. The simple form responds to the modernist aesthetics and the innovative use of the reinforced concrete by frame [21]. This early design is characterized by a spatial volume and a construction type with a main building material. The design concept is analyzed in terms of DPs that satisfy the defined FRs:

- DP1 = suspended, south-oriented, square-parallelepiped box pierced all round without interruptions
- DP2 = skeleton construction based on horizontal concrete slabs supported by columns

Unwanted couplings are checked by the DM (Tab. 3). Strong link is indicated by a large X and weak link by a small x.

	DP1	DP2
FR1	X	-
FR2	-	X

Tab. 3: First level DM

The resulting DM appears diagonal; the axiom one is satisfied. This design is uncoupled. Thanks to the one-to-one mapping between FRs and DPs, each FR is performed individually guarantying flexibility of the space and construction layouts and the achievement of the expected space and construction functionalities despite possible uncertainties. The selected construction type allows the independence of the construction function with respect to spatial layout. This result shows similarities to the Le Corbusier's strategy. He proposed a concrete system based on structural stilts and non-loadbearing walls (called "Domino") in order to realize different building solutions by the same prefabricated system [21]. This proposal shows the Corbusier's intent to move towards building prefabrication.

In AD the top-level FR1 is decomposed into a consistent detailed lower level identifying sets of compatible activities according to the architect's choices:

- FR1.1 = accommodate service activities
- FR1.2 = accommodate clients' living activities
- FR1.3 = accommodate clients' relax/contemplation
- FR1.4 = connect activities

The proposed solution is shown in Figure 3 [24].

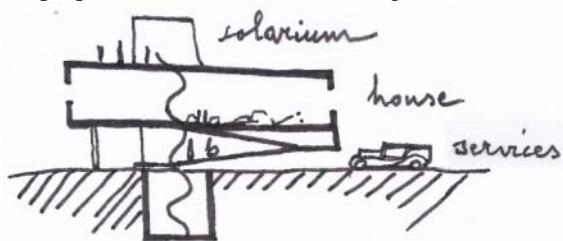


Fig. 3: Spatial design concept – section

It is made up of three clearly identifiable parts linked by an architectural promenade and a spiral staircase offering connection and changing views [23].

The DPs that satisfy the FRs listed above are:

- DP1.1 = semicircular service area at the first floor (entrance, small servant apartment and garage)
- DP1.2 = dwelling area at the second floor (L-shaped living-sleeping area facing on a hanging garden)
- DP1.3 = roof garden (terrace/solarium on the roof)
- DP1.4 = vertical connection area (in the centre of floors)

Unwanted couplings are checked by the DM in Table 4.

	DP1.1	DP1.2	DP1.3	DP1.4
FR1.1	X	-	-	x
FR1.2	-	X	-	x
FR1.3	-	-	X	x
FR1.4	-	-	-	X

Tab. 4: Second level DM - FR1

The resulting DM is triangular because the vertical connection area interferes with the fulfilment of the other FRs. Le Corbusier refined this strategy in following projects (such as the Pavilion Suisse at Paris) through building designs generated as modular architecture assemblies of separated functional volumes in which each volume serves a specific function [25]. He showed to apply the functional independence of FRs [25] as well as the one-to-one mapping between FRs and DPs in order to assure artefact robustness and flexibility from his viewpoint.

Also the FR2 is decomposed at the lower level into a minimum set of independent FRs to provide protection, safety, comfort and resources supply.

- FR2.1 = support loads and stabilize
- FR2.2 = separate interior from exterior
- FR2.3 = divide interior spaces
- FR2.4 = connect interior spaces
- FR2.5 = supply and manage resources

The proposed solution is shown in Figure 4.

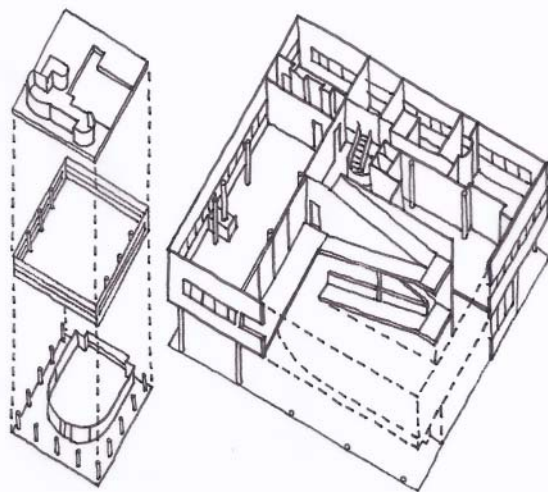


Fig. 4: Construction design concept – exploded diagrams

Le Corbusier showed in his writings the intent to apply the functional independence of FRs as well as the one-to-one mapping between FRs and DPs: “pillars, pipes, walls and staircase are each independent from the others. Pillars are removed from the walls of the rooms and are placed into the rooms. Also chimney flues are taken away from the walls and are placed in the centre of the room providing additional heat. Staircase is become a free element of connection. Since every physical component is independent from the others, each of them is capable of performing its own specific function at the desired level without reciprocal interferences [24]”. Moreover he believed that these elements could be easily mass-produced and erected in order to permit completion of every unit according to specific dweller’s needs [21]. This innovative approach founded its basis on the use of the reinforced concrete in form of frame.

By mapping, the solution is expressed in terms of DPs:

- DP2.1 = reinforced concrete loadbearing frame by pillars and floor slabs
- DP2.2 = reinforced concrete panels facades with long ribbon openings
- DP2.3 = interior partitions
- DP2.4 = ramp and spiral staircase
- DP2.5 = resources supply and disposal

The solution is evaluated by the DM in Table 5.

	DP2.1	DP2.2	DP2.3	DP2.4	DP2.5
FR2.1	X	-	-	x	-
FR2.2	-	X	-	-	-
FR2.3	-	-	X	-	-
FR2.4	-	-	-	X	-
FR2.5	-	x	x	-	X

Tab. 5: Second level DM - FR2

By the check of the DM, it is observed that most of the FRs is satisfied independently; some unwanted couplings between FRs and DPs are noticed. The matrix highlights that thanks to pillars and slabs, the interior space is freely configured by the architect without concern for supporting walls and openings on the facades. The loadbearing support does not interfere with shell and interior partitions. The facades are independent with respect to the supporting structure. Services systems are placed in view without incorporation into shell and interior partitions, but their arrangement depends on the shell and interior partitions configurations. The elements of connection (ramp and staircase) interfere with the loadbearing function. This analysis confirms that the functional independence between FR/FR and FR/DP pairs guarantees the achievement of the intended performances without limitations due to interferences. In this way architect is able to configure each physical component freely.

By this investigation, similarities between the results of the AD analysis and the Le Corbusier’s strategy are identified. This outcome has firstly proven the ability of AD to support early

architects’ decision making for addressing design towards solutions that are better able to be robust and flexible from the architect’s viewpoint. Secondly by the AD analysis, crucial early design decisions that affect the achievement of these requirements have been highlighted. They have been validated through the comparison with the Le Corbusier’s choices documented by his writings.

Case Study #2: Farnsworth House

Another modernist architecture house archetype and a recognized effort towards prefabricated architecture is the Farnsworth House (Fig. 5).

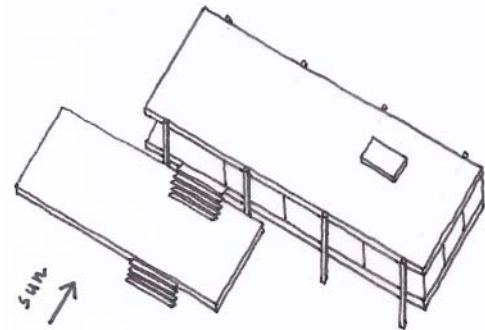


Fig. 5: Farnsworth house concept – axonometric view

The selected case study is a weekend house designed by Mies van der Rohe in 1946-1951 in the countryside of Plano (Illinois). It is placed within a large wooden land on a slope descending to the Fox River, facing south-west and parallel to the river. This house is a floating glazed rectangular-floor box elevated from the ground on steel columns in order to guarantee a better view and to prevent flooding [26]. It is subdivided (Fig. 6) into an exterior living area and an interior living area interconnected by a low flight of steps with a midway terrace.

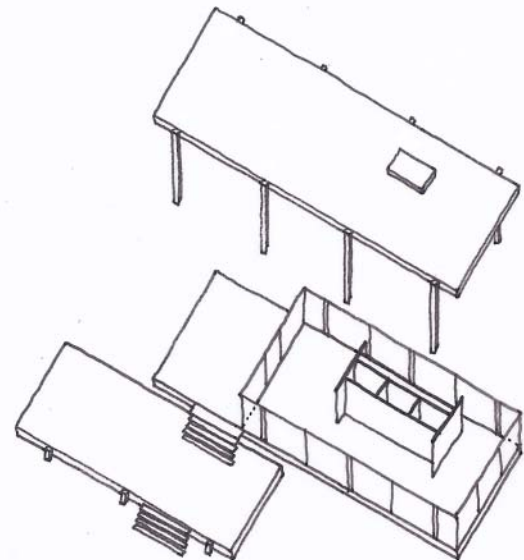


Fig. 6: Spatial-construction concept - exploded diagram

The exterior living area is composed of a covered porch and the entrance. The interior living area comprises a living area, a sleeping area and a kitchen space divided by a freestanding service core that accommodates a bathroom, a toilet for guests and a small installation room. The construction consists of eight wide-flanges steel stanchions to which are welded two sets of fascia channels to form a perimeter frame at roof and floor levels [27]. The building shell is unloaded. This allows realizing totally glazed shell in order to connect inside and outside visually [28]. Interior walls can be disposed freely, but since the house is planned for a single, interior divisions are only provided for the service core [29]. Service systems are placed between the steel cross-girders in the roof and floor slabs [27].

Mies van der Rohe asserted that dwellings should be designed and shaped in accordance with the desired performances and the chosen building material [30]. He focused on the aim of achieving robustness and flexibility from the architect's viewpoint in order to guarantee expected performances, satisfy different user's needs easily, and fulfill the architect's creative freedom. Mies van der Rohe asserted that the appropriate construction archetype is a structure able to transfer loads by punctual components such as a skeleton construction. In this way, partitions and shell are not involved as supporting walls allowing the free configuration of interior space and facades ("free plan" and "free facade"). He suggested setting mobile interior partitions in order to provide

flexible separation between rooms with the exception of kitchen and bathroom. These service rooms are instead arranged in a permanent location because of supply and disposal facilities. Moreover skeleton construction permits to optimize and rationalize building production process [30, 17] by industrial systems in which building parts can be factory-made serially and then rapidly assembled on-site [27]. This concept shows the Mies van der Rohe's intent to move towards building prefabrication. Moreover he proposed to provide central heating and hot water systems with pipes in view in order to permit future changes with easy [30].

Analyzing by AD the selected case study (Fig. 7), the results identified in the first case study are here stabilized: the functional independence of FRs and the one-to-one mapping between FRs and DPs support the development of a robust and flexible building design from the architect's viewpoint. The skeleton construction allows the free arrangement of space at the upper level, and then the "free plan" and "free facade" at the lower level. Some weak links are identified: the resource supplying function is placed into the roof/floor slabs and specific cavities, but its configuration is influenced by the loadbearing support and interior partitions layouts. Also in the second case study the architect's design strategy shows similarities with AD. These correspondences prove the effectiveness of applying AD to building design, and highlight crucial early decisions that affect the specified requirements.

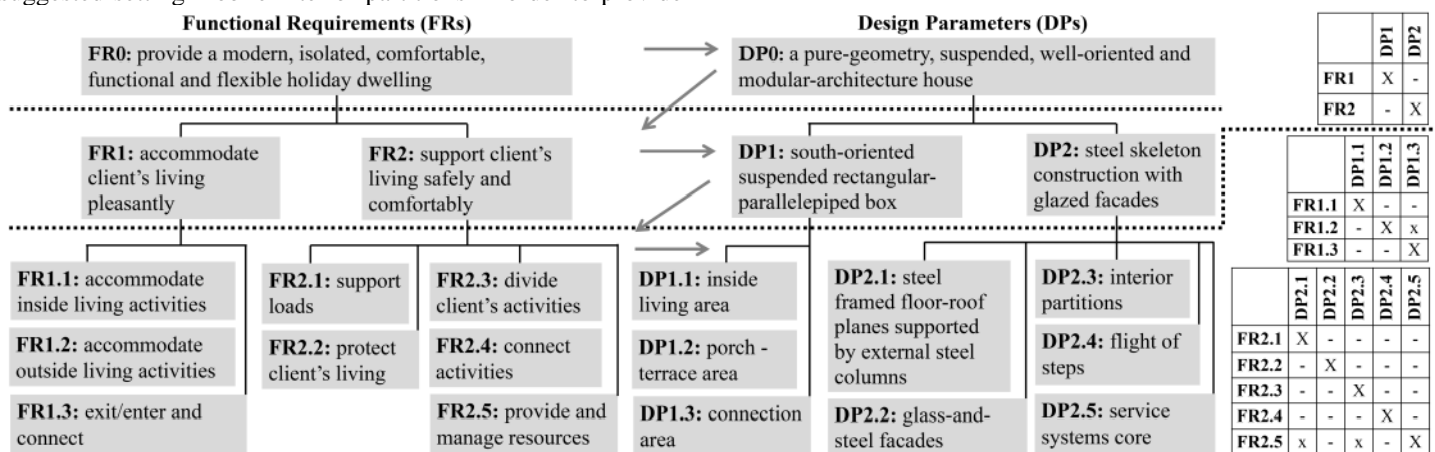


Fig. 7: Concept design analysis using AD

Case Study #3: Current Timber Construction Systems

This analysis takes into account the timber construction systems that are currently used by the Italian building industry. The aim is to verify their influence on robustness and flexibility of timber building designs. The timber construction systems in use are platform frame, loading panel, log and frame. This investigation considers a simple rectangular-parallelepiped prefabricated house, and supposes to employ and analyze each timber construction systems singularly. This investigation is performed by the sets of FRs identified in the analysis of the previous case studies. Related DPs are adjusted consequently.

Platform frame is a hybrid construction system made by linear members that allow each individual layer performing essentially just one function, but in this system, the loading and separating functions are united in the same plane within the wall. This system is composed of a frame of squared sections, an inner sheathing that carries loads and provides rigidity and an outer sheathing that closes the frame in which the thermal insulation is embedded. Therefore similarly to massive constructions, this construction system encloses directly interior space separating interior from exterior. At the same time, similarly to skeleton constructions, thanks to its linear member frame, it is characterized by design freedom

concerning interior layout, building shape and positioning of openings. Since this construction system is hybrid, there is a weak interference between space and construction at the upper level of the design process (Table 6):

	DP1	DP2
FR1	X	-
FR2	x	X

Tab. 6: First level DM

Then at the FR2 lower level, this construction system determines a weak interference between loading and separating functions lightly influencing their performances and flexibility. The loadbearing structure is usually not crucial for the clients' taste and therefore it could be mass-produced, but since it is combined with the facade that is usually decisive for them, the chance of mass customizing is restricted.

Loading panel and log systems produce massive constructions by walls that perform both loadbearing and enclosing functions. Since these systems create interior spaces directly and separate interior from exterior by walls, they determine a strong interference between space and construction at the upper level (Table 7).

	DP1	DP2
FR1	X	-
FR2	X	X

Tab. 7: First level DM

At the FR2 lower level, these construction systems determine a strong interference between loading and separating functions that strongly restrict robustness and flexibility. Moreover the chance of combining customized and mass-produced parts is strongly limited. Even though these weak points, the loading panel system is going to become the most employed timber system due to its large people's appreciation for marketing reasons and similarities with traditional massive constructions.

Frame system determines a skeleton construction composed of timber beam-pillar frames. In this system the construction function is not affected by the space configuration because the frame system does not separate interior from exterior, and it does not influence the creation of interior spaces. At the upper level, interference between space and construction are not observed (Table 8).

	DP1	DP2
FR1	X	-
FR2	-	X

Tab. 8: First level DM

At the FR2 lower level, the interference between loading and separating functions is not observed. It is able to support the mass customization strategy. Despite its effectiveness, this system is not commonly used by the timber building industry.

DISCUSSION

This case studies analysis has shown firstly the ability of AD to support early architects' decision making for addressing design towards solutions better able to be robust and flexible from the architect's viewpoint. Secondly it has identified crucial early design decisions that affect the achievement of these requirements. In particular it has observed that the capability of building solutions to perform the specified requirements is fostered by the functional independence between space and construction and by the functional independence between the related sub-systems.

At the upper level of the design process, the functional independence between space and construction guarantees the achievement of the attended space and construction functionalities in spite of changing customers or functions or physical components as well as the flexibility of the space and construction layouts. The functional independence is achieved by the use of skeleton constructions. At the lower level, the functional independence between sets of compatible user's living activities fosters the fulfilment of attended space functionalities. Moreover the identification of decoupled spatial modules allows variations on the spatial layout according to different clients' preferences and contexts. Finally the functional independence between construction layers allows the sure achievement of the required construction performances without compromises due to interferences. Further this condition supports the chance to easily adapt construction layers according to different clients' needs and context features.

In the timber building industry, the timber construction systems mainly applied determine interferences between space and construction at the upper level of the concept generation and between construction layers at the lower level. The platform frame system determines weak couplings slightly limiting the design robustness and flexibility from the architect's viewpoint. The loading panel and log systems produce strong couplings limiting the effectiveness of designs with respect to the specified requirements. Instead in the timber frame system interferences are not observed at the upper and lower levels. Although it appears to be the best construction system for the development of designs that satisfy the specified requirements, this system is rarely used.

CONCLUSIONS

This research asserts that Italian timber building industry should focus on robust and flexible buildings from the designer's viewpoint to satisfy the current demand for affordable customized housing. Therefore design robustness and flexibility from the architect's viewpoint are crucial requirements. They are set in the conceptual design phase, but this stage is not adequately supported. Since AD supports the analysis of design concepts with respect to the specified requirements, this study has applied AD to the review of well-recognized prefabricated housing archetypes. By AD, crucial design decisions adopted by architectural masters and affecting artefact robustness and flexibility from the architect's

viewpoint have been identified. It resulted that these requirements were fostered by the functional independence between the defined space and the chosen construction at the upper level of the concept generation and by the functional independence of the respective sub-systems at the lower level. Then this analysis has examined the timber construction systems commonly used by the timber building industry. It has resulted that timber building industry is investing in construction systems (especially the loading panel system) that limit the effectiveness of design with respect to the specified requirements. According to the results of this analysis, timber building industry should review the construction systems commonly used focusing on skeleton constructions and the functional independence of the physical components. In addition, according to AD, connections between physical components should be decoupled in order to enhance artefact flexibility. By this scheme, timber building industry may be better able to develop robust and flexible designs in order to satisfy the current housing demand through building solutions in which customized parts are combined to mass-produced parts. In this manner, clients may have the chance to personalize crucial parts for them, and building industry can limit building costs by the mass-production of the others.

In future, the research intends to apply AD on the redesign of timber prefabricated building systems in order to enhance them with respect to the specified requirements and therefore to provide building systems better able to satisfy the current housing demand.

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