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Reversible Architecture for a Sustainable Future. Finding out Key Design Guidelines in Early Disassembled Systems

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As a part of the ecosystem, humans actions are forced to integrate within the natural biological cycle. As an answer to the social, environmental and economic challenges, both architects and builders are asked to adopt new building methods. From the baseline option of building systems to have the capacity of being disassembled so their components can be reused, processed, and reassembled, the main discipline that can tend to this issue is reversible and demountable architecture. The construction of the physical boundaries of the building will define the possibility of disassemblage of each element, understanding the construction as an assemblage of pieces in which joints become the most important part regarding shape and structure.

This research is based on the identification and the analysis of the main permanent building systems with high potential of disassembly erected through time. Beyond the conclusions reached by studies focused on experiences of recent years, this study intends to start in the ancient eras. The first stage is based in those systems built in the early ages up to the times of the Scientific Revolution. There we can find in a clear and obvious way the precise balance in the correspondence between elements, space, form and function, obtaining the proper integration for each environment. On the second stage it is intended to assess the evolution of each solution and to establish its connection with more recent ones. Three different phases (documental, analytical and propositive), are developed for a proper completion of this study.

There is no construction system that has completely disappeared after its invention. Essential innovative technologies remain active even they may continue to exist only in small areas, or only for supporting periodical renovations. Every construction system applied in the present supports its equivalence with another used in the past. Following this discussion, a careful reading of ancient architectural systems is able to provide the basis to define the design guidelines of reversible architecture for a more sustainable future.

KEYWORDS: construction process, disassembly, past, reversible, system.

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Introduction

Disassembly in sustainable design

Reversible, from latin *reversus-reverti*, is referred to what may be altered or changed to return to its previous state or condition retracing its steps. Disassembly will be considered as the act to take to pieces, to take apart.

Biological designs are determined by energy, adopting solutions according to the environment in order to obtain the maximum benefit with the minimum sources. Natural designs are optimal. And in this natural environment every element is necessarily incorporated into a biological cycle (Araujo, 2009). Waste from some sources becomes a source itself. Also, human actions are inexorably bound to be integrated in this process, leading to recover and reuse everything we manufacture and produce, and properly return it back to our environment. In this sense, reversible and demountable solutions are one of the best answers to attend this proposal.

The possibility embodied in the process of construction, use, maintenance and deconstruction while renewing resources, is the main advantage offered by these solutions. Remove and *leaving no trace in the landscape* while taking and recovering materials and components. And this renewal process, which may occur both in the biosphere and due to human initiative, will provide better results when performed under this second option. Settlements in the South of Morocco are built with soil. When their life cycle is coming to an end, the natural environment is able to recover the resources that were previously extracted for their construction. Materials and elements return to the biosphere reintegrating back into the landscape. The same principle is found in those proposals built with natural lightweight elements. Nature will take care of recovering what was borrowed before. Although these are unquestionable cases of environmental renewal, here “deconstruction” does not require human intervention.

Fig. 1

Left: Valley of the Draa, South of Morocco | Center: Kasbah in Tamnougalt,Valley of the Draa | Right: Congo River, Bounda. Sources: www.desertcampmorocco.com | www.yannarthusbertrand2.org

Building demolition procedures used today tend to recycle the main part of the building waste, that will be reincorporated back into the transformation process for obtaining materials. But in this deconstruction process, most often than not entire parts of the building systems are not recovered; components are not disassembled nor reused (Sobek, 2014). In response to social, environmental and economic challenges, the building sector is forced to develop new construction methods. Instead of demolish structures, building systems can be disassembled and their components reused, processed and reassembled in new combinations. Designing for later disassembling, when adopted from the early stages, involves the use of materials and systems ready to be reused and recycled, recovering the materials themselves, and finally the energy they contain. This approach would allow existing buildings to serve as raw material for new construction, replacing the resourcing of the natural environment.

What is prefabricated or removable nowadays has a high negative connotation for end users. The clarification of the actual performance of these systems and their adaptation to the temporal and economic demand, are the key for these systems to become competitive when compared with traditional solutions that are generally accepted.

From architecture to piece

Based on its technical side, construction consists in the assembly of pieces, which will merge into the physical boundaries of the envelope built (Seco, 1998). In this context, joints become the most important element involved in the definition of the shape and the structure of the building. Dry and mechanical connections are the joints that can be disassembled, where pieces that are intact in form and dimension are connected. The result is an assemblage of parts that is perceived as a whole system and that define the building as being composed, with each part needed and nothing superfluous. Opposite to this, chemical connections are those that cannot be broken without altering members therein coincide and resulting in a whole by continuity of the joined parts. The relation of the parts together and with the whole building, as the physical evidence of the construction process, proportions of elements and materials employed, is established as an essential factor for a proper understanding of every work of architecture.

From the earliest eras, the technical evolution of the construction elements and their joints has been based on the material and functional specialization of the connections. Ancient Architecture had the advantage of the limitation on the amount and variety of materials employed. This would result in a greater uniformity of the building, in which simple joints would provide the base for the develop of simple and uniform construction systems. In this context, the selection and assessment of those solutions, where the clear and universal balance among parts, joints, form and stability of the building exists, and where the assembly method allows to be dismantled, has been carried out. Beyond temporary proposals, emergency solutions or nomads lightweight constructions, the focus of this research will be focused on permanent architectural solutions with high potential of disassembly.

Searching in the past

Research intends to start from the beginning. It is in ancient classical architecture, and also in traditional architecture, where we can find in a clear and obvious way the precise balance in the relationship between elements, form and function, obtaining the proper integration for each environment.

Starting with the systems built with dry joints by using simple vertical loads, as those of Ancient Egypt or Ancient Greece, they will evolve with the introduction of the Roman arch and dome, and the active joint between its parts. During the Middle Ages the mortar joint will be necessary for laying the irregular parts of the churches walls, and will be also used in the construction of the flexible skeleton of Gothic cathedrals. Regarding wooden construction, Oriental temples and Norwegian medieval churches or "*stavkirke*" are definitely cases to be highlighted.

Lightweight will be the main goal of the construction systems of Modern times, in order to search for building efficient designs. A large amount of elements and joints will be developed in this period, taking to blur the piece in a complex set of connections, as it happens in the iron architecture of the 19th century. The evolution of modernity will be based on the introduction of new materials and the specialization of the elements according to their function within the building.

Every construction system applied in the present supports its equivalence with another used in the past. Following this discussion, a careful reading of ancient architectural systems is able to provide the basis to define the design guidelines of the reversible architecture for a sustainable

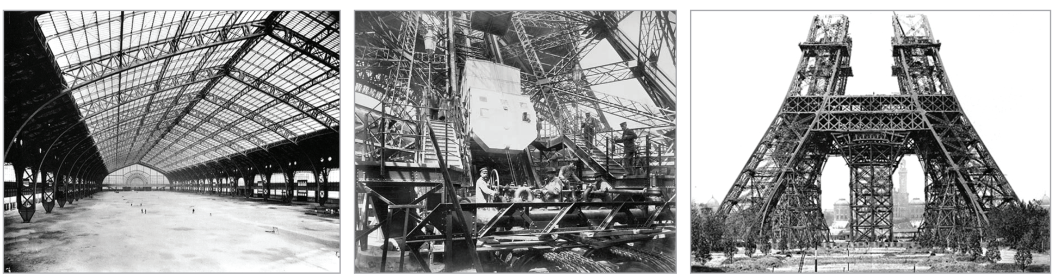

Fig. 2

Left: Galerie des Machines, F. Dutert. Paris 1889 | Center and Right.: Tour Eiffel, G. Eiffel. Paris 1889 future. Obtaining the correspondence between them, and the integration of their advantages will be the goal of this project.

Writings and theories on assembly systems

Looking for the theoretical compendium about the art of building in ancient times and its assembly systems, the first treatise on architecture is *De Architectura.* Written by Vitruvius in the 1st century B.C. and found in Saint Gall in 1415, it would have greatly influence in the architecture of the Renaissance. The traditional practice would cease to be the true source of knowledge to be replaced by the authority of classical architecture.

The intense activity of quarrymen in the Middle Ages would lead in the 16th century to specific treatises to detail the shape or shapes of each piece. They were written by architects and master builders for their apprentices, without being intended for publication, containing sheets with geometrical parameters for cutting and placement of parts (Mark, 2002). *Instructions*, written in 1516 by Lorenz Lechler, master builder of Heidelberg, included not only geometric patterns but also specific advice on structural details regarding thicknesses, spans and dimensions. The term "stereotomy" would begin to be used in the 17th century and would refer to the art of cutting stone and wooden pieces to put them in place. From 19th century it also applies to iron.

The employment of these early treaties led to the standardization of the architectural design. The conservative tracing of the writings up to detail drowned the structural and constructive innovation in these periods.

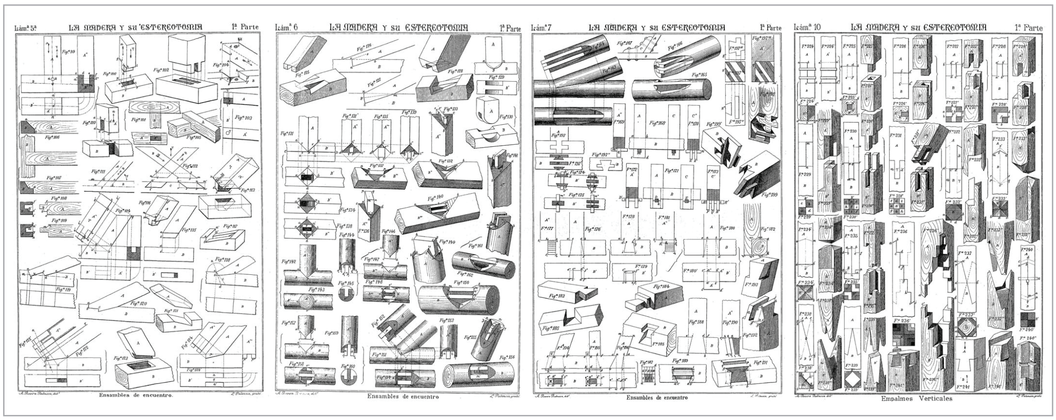

Fig. 3

Treatise: "*La madera y su estereotomía*". A. Rovira y Rabassa. Barcelona, 1900

Choisy (1970) included complete descriptions about the construction techniques of the cultures of the early days in his texts. Viollet-le-Duc (1998) and Heyman (1995) described in detail the way in which the medieval structures work. In the 19th century the Treatise of Rondelet gathered the knowledge from all previous construction systems, becoming mainly practical. At the beginning of the 20th century the technological progress and the emergence of new materials and systems led the overcoming of tradition and its treatises. Building construction would take in this moment a very different way regarding the past, becoming a mainly experimental science based on trial and mistake, and would soon have their own manuals.

The module and the modular coordination, and their applications, will have a key role in this theoretical background. The Crystal Palace of Joseph Paxton, built in 1851, was the first application of the modular coordination in the new industrial setting. But the module was already used in the early architectures, searching for the beauty in Classical Greece, with an aesthetic and functional sense in Ancient Rome, and in a decidedly functional way in Japanese architecture. The studies developed at the end of the Second World War, with the octametric module of Neufert, the French standard of 1945 or the module of Lescaze and Davison as main references, will drive the way for the incorporation of the Modular Coordination as strategy for architectural design, and as a means to optimize the three main factors in building construction: time, cost and quality.

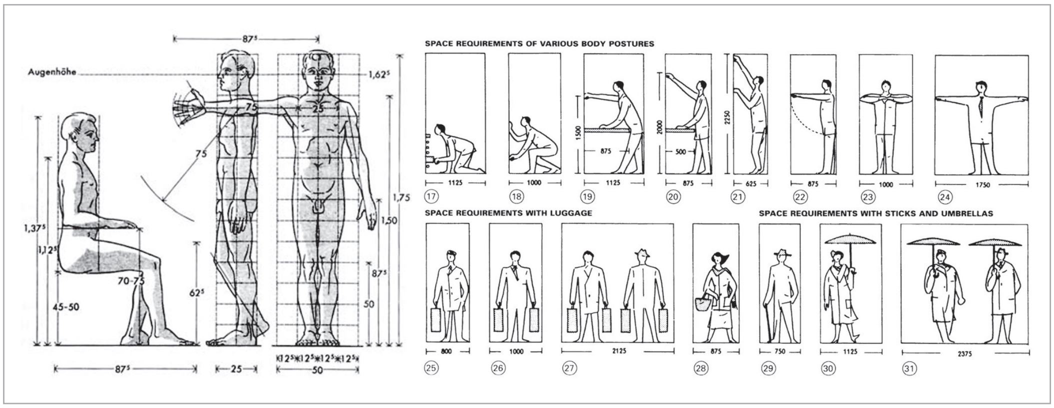

Fig. 4

The proportions of man in the "Oktametermaß", E. Neufert, 1943 | Right: *Bauentwurfslehre*, Neufert, ed. 1991

In 1960 Habraken introduced his concept of "levels". A building would be comprised of two levels: the support level and the infill level, being able this last one to change and improve over time. Duffy and Brand (1998) will complete this approach, including the temporal factor related to the lifecycle of the building components in redefining the different levels.

The proposals of the last years are focused on demonstrating the reduction of environmental impacts arising from the use of disassembly solutions. Several studies such as those conducted at the University of Delft will aim to promote the change and transformation of the building structures from the use of independent systems, creating a basis for the widespread use of open structures.

Building systems with high potential of disassembly

Building systems with high potential of disassembly in ancient and traditional architecture. 1st period – from Antiquity to Scientific Revolution

In order to proceed with the identification and analysis of the main cases related with the reversible architecture built in the past, the first stage is focused on the First Ancient Civilizations.

The architecture of Ancient Egypt was huge either on each of its parts and on the whole, and also solid and durable. From *c.*3150 B.C., it has endured to the present day notably influencing the progress of history. The main elements that appeared, there would be then part of the architecture of every civilized nation: columns in proportion joining lintels made of stone, and supporting two-ways spanning slabs, all with an extremely monumental decoration.

In Ancient Greece a mature architecture, master of its tools and its effects, was developed. A clear understanding appeared here between form and construction. To achieve beauty while also rationality in construction was the ideal of this period. Based in the architecture of the previous eras, the volume and weight of construction elements employed in this period was notably smaller than those used in Ancient Egypt, so it would be necessary to adapt them to the new conditions (Coulton, 1977).

In the construction systems of these two ancient eras, the main joint employed was the simple support, which would lead to the elemental span (Seco, 1998). The aim of this joint was only the transmission of vertical loads, for any other force would break the connection . The scale of the buildings and the increasing amount of parts would result in the 5th century in the addition of staples and metal studs to ensure the proper placement of the elements and the absence of gaps and displacements in the structures.

In the 2nd century, builders from Ancient Rome started to use the arch and its developed forms: the vault and the dome. The horizontal pressed joint was able to evolve to the vertical one, due to the introduction of the active joints between parts. The dissolution of the Roman culture in the beginning of the Middle Ages would cause the application of rushed and immediate solutions. The mortar joint would be included then for the geometric alignment and the correct laying of the irregular stone parts (Mark, 2002). Gothic builders, in their proposal of make independent the structure and the envelope of the building, continued using this mortar joint that would be called the "rubber joint" (Heyman, 1995) of the new elastic wall that could actively respond to the variations of the load conditions.

In these first eras, wood and stone were shaped to be placed precisely. Assemblies of parts that came from the quarry or sawmill would lead to the typification of the joining details. Classical Greek orders will be built as a literal translation of wooden details to stone ones. The shape of the simple square stone pieces forming horizontal or vertical surfaces in Ancient Egypt would evolve over the centuries up to the ingenious stonework of Gothic architecture. At the same time, wooden construction made by connecting pieces modifying its borders, would be developed taken as main references the Oriental wooden architecture and also the architecture of the Nordic medieval villages. In fact, these wooden construction methods are still used today.

Regarding the cases studied for this first period, the most representative ones include the Great Pyramid of Giza (c. 2570 B.C.) and the Amun Temple in Karnak (c. 2200-360 B.C.); Temples in Thermos, Aetolia (c.880-625 B.C.), Apolo Temple in Bassai (430-400 B.C.) and Hieron of Samothrace (340-317 B.C.); Theater of Italica (1st century B.C. - 1st century A.D.); Yakushi-ji Temple in Japan (680 A.D. - 698 A.D.) and Gol Stavchurch in Norway (12th century); Reims Cathedral (1211 A.D. – 1275 A.D); and the "petit bois" trusses developed by Philibert de L´Orme in 1561.

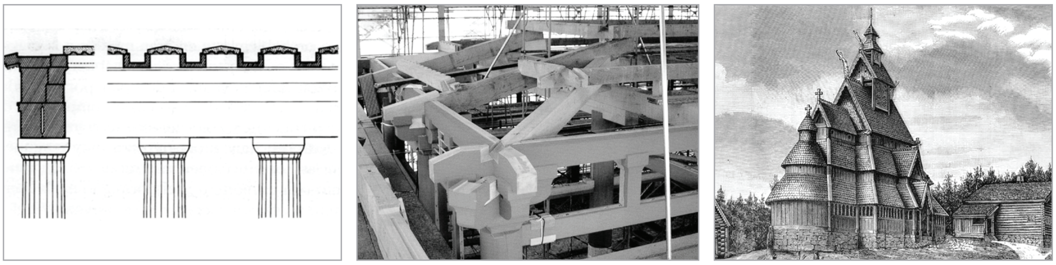

Fig. 5

Left: Apolo Temple in Bassai. Section (430–400 B.C.) | Center: Yakushi-ji (680-698 A.D.) | Right: Gol Stavchurch in Norway (12th century). Sources: Coulton J.J., 1977. | Azby Brown S. The genius of Japanese Carpentry. Tokyo, Kodansha 1995. | http:// norskfolke.no

Equivalent systems with high potential of disassembly in recent architecture. 2nd period – from Industrial Revolution up to the present

The construction in the modern era was based on the separation between structure and non-bearing walls. The joint solved by vertical simple support would not be used. New resistant connections had to respond to multiple and different loads. The maximum size of the single structural element increased due to important technical advances. The wall, either as multilayer section or made with framework elements and boards, had to respond to more qualitatively different requirements. Thus, connections would acquire a high level of specialization and complexity. Steel, glass and concrete would become the main materials, gradually introducing other new artificial materials that cause the diversification of the tensions supported the joint, coming at the end of their possibilities to the total substitution of the mechanism by the material (Seco, 1998).

The industry adopted a key role in the building construction of the modern era. Methods brought from factories and mass production industries would be applied in the search for faster, more efficient and better solutions than those obtained by traditional construction methods (Araujo, Azpilicueta, 2012). In response to the industrialization of single systems and components not always compatible to each other, in the mid-twentieth century some proposals emerged aiming for the industrialization of the entire building. In these projects the building became an integrated system in the search for a model to be repeatedly built. Prouvé or Fuller proposed the prefabrication of entire small buildings, focusing on single houses. Other proposals were also be developed in collective housing. But these attempts would not succeed

Today there is wide range of industrialized building systems. They can be classified in closed, partially-open and open. The scale of the proposal will determine the way of assembly and the selection of the system. Tridimensional modules will be used mainly in small buildings as single houses, systems based on prefabricated panels will be applied in small and medium buildings, and lightweight structures with independent facades in large proposals as dotational buildings and office buildings. In collective housing the building will become an experimental area where to test the compatibility of different types of patents. The percentage of off-site fabrication will be increasing in all these solutions.

Representative cases of this period include the balloon frame system used for the first time in Chicago in 1833, the Crystal Palace of London (1851), the Aluminaire House designed by Kocher & Frey in New York (1931) and the Lustron House of Strandlung Co. (1948); the brick arch experiment developed by Frei Otto in 1950 and the wooden geodesic dome proposed by Buckminster Fuller in 1954; the Toyota Home (1978) and Muji House (2004) produced in Japan, and the ICD/ITKE Research Pavilions developed in Stuttgart University from 2010.

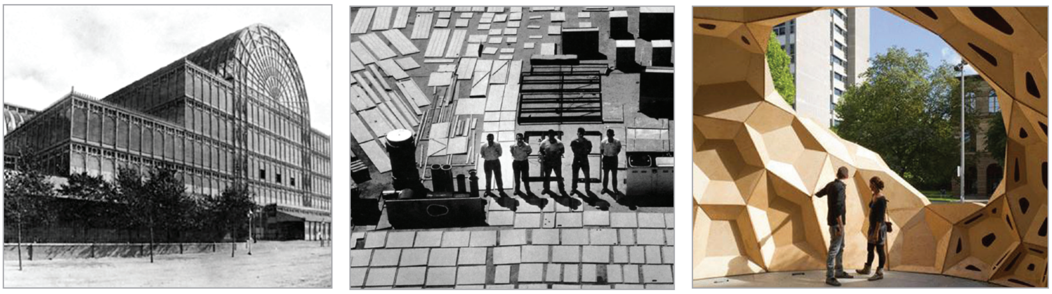

Fig. 6

Left: Crystal Palace (J. Paxton, 1851) | Center: Lustron House (Strandlung Co., 1948) | Right: ICD/ITKE Research Pavilion (Stuttgart University, 2010). Sources: www.studyblue.com | www.trianglemodernisthouses.com | http://icd.uni-stuttgart.de

About proposals for the future

The new digital technologies for shaping pieces, and the high level of supervision in the fabrication and assembly procedures, represent the present and future state of the building construction industry. These procedures are providing the architect with a wide range of products and possibilities for designing suitable solutions for the next future.

The concern for obtaining energy efficient buildings is inviting us to think about new proposals for the future, and places the disassembly and reuse of components as a key part of the building process. Parallel assembly of the building parts will be often more suitable than sequential one in order to facilitate the possibility of subsequent disassembly. The multi-component building elements used today in building construction, difficult to separate into their original components at a reasonable cost (Sobek, 2014), could be replaced by independent elements that maintain different functional expectancies within each construction system. The connection technique used plays a decisive role here, with the dry joint as an unquestionable main character. If the current trend which is to minimize the auxiliary elements within the connections that are joining the building elements continues, the recovery and adaptation of the concepts used in ancient and traditional architectures will provide architects and designers with an important knowledge to be considered and therefore applied.

The challenge is to turn the building into a coherent set of parts that are assembled and disassembled clearly and without difficulty. And this goal should be achieved from a conception of the building as a whole system.

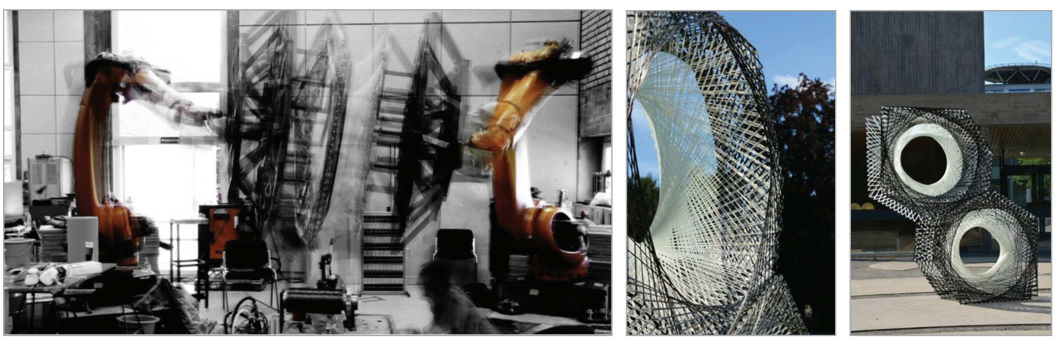

Fig. 7

CD/ITKE Pavilion 2013. Manufacturing pieces made of glass fiber cords and carbon fiber cords using KUKA robots. Universität Stuttgart. Source: http://icd.uni-stuttgart.de

Conclusions

From the identification and analysis of the early building systems with high potential of disassembly included in this study, it is possible to obtain a set of overall conclusions.

The evolution of the construction systems of these early eras was clear and continuous. Builders from these first periods would not hesitate to provide construction processes with all their skills and all their ingenuity. Thus, practice of medieval builders would come to lay the foundations of the construction of modernity. They always advanced, overcoming their own mistakes and learning from them, adapting and improving their techniques, based on the experimental method rather than blindly follow the ancient tradition. It would be irrational and inappropriate trying to build today as they did in the early days, but the experience gained by those builders can serve us really useful, since such masters were great innovators. The extreme care in the design and the execution of all dry assemblies of the buildings would provide outstanding results.

There is no construction system that has completely disappeared after its invention. Essential innovative technologies remain active even they may continue to exist only in small areas. The solutions included here were built to endure over time. But, at the same time, its initial design also contained a high potential for disassembly. The lesson for the present is that when such systems are well thought out and executed not involve a loss of strength and durability, but rather the opposite.

Today the building industry is able to offer considerable technical breakthroughs, including the most advanced digital manufacturing processes. In this context, the incorporation of criteria about dismantling, interchangeability and adaptability of components from the earliest stages of design may result in buildings with a high capacity of spatial adaptation and technical functionality, but and at the same time, will lead to one of the most sustainable options for building the future.

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