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Lightweight Technologies in Sustainable Architecture: The Importance of Connections in Disassembly

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Abstract: The aim of this paper is to investigate the role of lightweight structures and connections in the DfD (design for disassembly) framework. The construction sector is facing pressure to reduce its environmental impact, which has led to heightened interest in DfD as a strategy for transitioning from a linear "Cradle to Grave" economic model to a circular "Cradle to Cradle" model. At the social level, DfD's technological and spatial flexibility provides opportunities for self-build and self-maintenance processes, which can decrease land consumption and reduce costs for both owners and tenants. In this context, lightweight structures and connections are crucial for enabling these processes. The methodology used for analysis involves breaking down three technological elements chosen from three different projects to evaluate ease of disassembly, flexibility, potential for reuse, and recyclability. As a result, this paper aims to promote the development of an abacus of existing technological solutions, to provide designers with a tool that can help them pursue DfD strategies.

Key words: Circular economy, sustainable architecture, DfD, connections, lightweight structures.

1. Introduction

The linear economic model (take-make-use-dispose), which is mostly applied in today's industry, considers the Earth as an endless reservoir of raw materials that can sustain world production forever. This approach has had and is still having very negative impacts on the environment, both in terms of the consumption of natural resources and in terms of energy consumption and greenhouse gas emissions.

To counteract the effects of climate change and achieve the decarbonization goals of the Paris Agreement (2015), it is necessary to take action in the main carbon-intensive sectors, one of which is the construction sector. On a global scale, buildings are responsible for producing around 40% of all waste, using 40% of all extracted raw materials, and emitting approximately 33% of all emissions [1].

The linear approach in the building and construction industry involves the extraction of raw materials from the environment. These materials are then transformed into building materials and components, which are mainly assembled on site using traditional construction techniques, making it difficult to disassemble and apply circular economy practices [2]. During the building's use phase, issues related to the design process often arise. The building design is oriented to the creation of the building, ignoring concepts such as Flexibility, Adaptability, and Disassemblability in most cases. These concepts play a crucial role in preventing the obsolescence of the building and promoting a circular economy model. The end-of-life phase is particularly impactful on the environment, as most buildings are demolished, leading to large quantities of waste, C&D (construction and demolition) waste [3].

The key principle of the circular economy is to decouple economic growth from the overuse of natural resources, thereby minimizing negative environmental and social effects [4]. This is achieved by keeping materials in a closed loop using circular practices, such as reuse, recycling, and reconditioning, to prevent loss of value [3]. It is evident that shifting to a circular

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model is a current and prominent topic, as evidenced by the significant amount of scientific literature attempting to create specific definitions for the circular economy in the building sector [3, 5, 6]. Despite this, it appears that there is a lack of awareness of the potential benefits that a circular economy model can bring to the sector [7], which hampers its implementation.

To develop a circular economy in the building sector, the design process must be renewed to encompass the entire life cycle of the building [1], including the end-of-life phase. This approach should aim for flexibility and adaptability, while ensuring that resources can be reused in the future. The concept of keeping materials in circulation, rather than extracting new raw materials, means looking at existing building stock as a temporary repository of materials and components that can be used to meet future demands [1]. The framework of Design for X, in which DfD (design for disassembly) is the most studied and deepened, appears to be an interesting strategy to achieve these purposes, allowing introducing circular economy practices since the first phases of the design process. This method, originally developed for the production of consumer goods, has been gradually adopted in the construction industry and is seen by some as a driving force for shifting to a circular economy model [6]. In this context, many building sustainability protocols, such as LEED and BREEAM, are beginning to adopt DfD as a parameter to evaluate circular building performance.

Besides the environmental benefits that DfD is capable to bring to the building sector, it is interesting to deepen its social benefits. Nowadays, the increase in global population we are facing requires buildings to be flexible [8]. This is fundamental to avoid intensive exploitation of soil and buildings becoming outdated due to the impossibility of satisfying occupants' needs. In residential buildings, DfD makes it possible to establish owners or tenants as active players in transforming the building, by providing proper instruction and encouraging self-building. To achieve this goal, it is important to deepen our knowledge of the main technological component that enables the disassembly of the construction, the joint, which is considered the minimal building block of DfD. This article aims to examine the role of structural and architectural joints in the context of DfD. To do this, it provides a historical background on various types of dry connections used in the past, as well as an analysis of three case studies. The case studies were analyzed using a methodology that involved breaking down the analyzed systems to gain a deeper understanding of their technical details and complexity. Through this analysis, our aim was to comprehend their behaviour and level of disassemblability.

2. Method and Materials

2.1 DfD and Brand's Model

DfD is a concept that has its roots in the industrial sector and it is being explored for use in the construction industry. Climate change is driving the need for a shift towards more sustainable building practices and technologies. As a result, DfD is once again gaining attention as a viable strategy for promoting a circular model in the AEC (Architecture, Engineering, and Construction) sector.

Examples of DfD can be seen in various architectural traditions, including the archetype of the primitive hut by Laugier [9], vernacular architecture in Europe, China, and Japan, and buildings constructed for universal expositions such as the Crystal Palace (1851) [10, 11]. These structures are characterized by demountability, the use of dry construction techniques, and lightweight structures. The joint is a key component, which holds structural and architectural significance in timber construction, particularly in the outstanding cases of Chinese and Japanese architecture.

The concept of DfD was formalized for the construction industry in the late 1990s and early 2000s [12]. The core idea behind the strategy is to make buildings disassemblable, a feature that enables engineers and architects to consider the entire building life cycle in their design. The process of disassembling not only allows for repurposing the space, but also for replacing or upgrading components and systems. In other words, it makes the building flexible in both technology and space. Flexibility plays a key role in conforming buildings to occupants' needs, thereby extending the building's life cycle. On average, buildings have a long lifespan, ranging from 50 to 100 years, and some building components are designed to last even longer than the building itself. However, at some point in its life, the building becomes the subject of a choice that dictates its total or partial demolition or abandonment. According to Crowther [10], this happens due to obsolescence, which can take the form of locational, functional, fashionable, physical, or technical reasons.

The deconstruction of the building challenges the widespread view of static and permanent construction and opens up the possibility for change. Designers should start to think about buildings as temporary objects [13]. Nowadays, it is essential to design buildings that are capable of adapting to the rapid changes they face, such as the recent COVID-19 pandemic.

A major factor that deserves attention from the scientific community is the possibility of facilitating disassembly to the extent that routine maintenance, extraordinary maintenance, and self-build operations can be carried out by owners or occupants. This is an interesting insight from a social perspective, especially in light of the future demand for housing that will arise from global population growth. It is important to note, however, that in order to foster self-build and self-maintenance operations, structural types, materials, and components must be lightweight.

Many researchers have studied the DfD strategy, and among them, Guy and Ciarimboli [12] have produced a list of ten key principles to follow in order to create demountable buildings. Among them the importance to compile a "deconstruction plan" is paramount. Through that designers must provide detailed information about the disassemble process, in order to simplify it and to avoid mistakes. Drawings and labels of connections and materials must furnish the plan. Authors stress the importance of connections. They must be visually, physically, and ergonomically accessible. Additionally, it is recommended to use bolted, screwed, or nailed connections to facilitate disassembly and encourage the reuse or recycling of salvaged components. Designing to facilitate the work of separating components is crucial. It is recommended to use human-sized components to reduce the effort required and allow people with any skill level to carry out safely disassembly tasks. The principles outlined in this research are of crucial importance, as they establish the idea of accessibility and constructive simplicity necessary to encourage self-sufficient maintenance and construction operations. The aforementioned principles are crucial for the purposes of this research. What emerges is the duty on the part of the designer to extend the project to the whole building life-cycle, through the deconstruction plan. It also becomes evident that there is a desire to establish a more democratic scenario where the owner or tenant can easily perform maintenance and construction operations.

Time is a crucial factor in the DfD approach. The technology systems used have different lifespans. Hence, it is important, especially for maintenance purposes, to separate these systems and make the shorter-lived ones more accessible in the building by placing them near the surface. The model suggested by Brand [14] (the "six S") is a paradigmatic model for dividing different building layers [12, 15]. The model identifies six components: soil, structure, skin, services, space plan, and stuff, each with varying lifespan ranges. Soil and stuff are at opposite ends of the spectrum, with soil considered eternal and stuff changing daily or weekly.

To allow disassemblability and foster flexibility, it is desirable that the technological units in the skin, structure, and space plan have high levels of technological flexibility. This can be achieved through accessible and durable connections. Building's joints must also be capable to withstand different mechanical stresses. This paper aims to study some of the lightweight structural types and connections that are suitable for the technological units in the layers. They are contextualizing within the DfD strategy, in order to evaluate the level of expertise needed for assembly and disassembly operations.

2.2 Lightweight Structures and Connections: Historical Notes

The discussion about lightweight structures presented here begins by giving an historic overview of the role of joints and lightweight structures.

Chinese (Fig. 1) and Japanese architecture is characterized by an abundance of lightweight structures and dry connections, each crafted to fulfill specific needs. To solve the problems caused by severe weathering in China and earthquakes in Japan, new lightweight technologies were developed to optimize resistance and displacement while reducing the harmful effects [11]. In China, a projecting system, called dougong, was implemented to increase roof projections and reduce the building's exposure to the weather.

This system was made up of wooden elements connected through semi-rigid joints. Such a system is known from 770 BC [11]. In Japan, the structural systems used were based on the tenon-mortise dualism, where vertical and horizontal wooden elements formed the building's structural frame and the connection between the elements was the most interesting feature to analyze. The joints needed to ensure both elasticity and strength during seismic events. The use of wood ensured elasticity, while the different variations of tenon and mortise are provided by Japanese carpenters, chiang-jen, provided varying levels of movement and strength [16]. In Europe, the widespread use of timber framing coincides with the appearance of mortise and tenon joints during the 15th and 16th centuries. Along with dovetail and halved lap joints, these are the most popular types of connections used in half-timbered buildings, widely found in northern European countries. Interestingly, these connections not only ensure good static performance, but also provide impressive ornamental function [11]. Despite their complex nature, which is the result of technical knowledge passed down through generations of carpenters, these systems offer a useful starting point for developing new types of dry connections for DfD. Note that connections, such as tenon-mortise or dovetail connections, that rely on direct interlocking of one element into another, may not be durable with frequent disassembly. The material becomes a critical factor in balancing durability and sustainability in this case.

During the Industrial Revolution, steel and cast iron emerged as construction materials and were mainly used in public buildings and infrastructure. The Crystal Palace, for example, which was built for the first World's Fair, was disassembled and reassembled using a special system that involved interlocking beams and pillars through wedges [17]. Up to four cast iron lattice trusses could be placed on top of each. The Eiffel Tower (Fig. 2) used rivets to connect metal trusses, with connection plates welded to other structural components. Today, these connection techniques are still widely used, but with bolts. In more recent times, Buckminster Fuller's research on spatial symmetries of regular polyhedral led to the design of lightweight, prefabricated, and

Fig. 1 Forbidden City, Beijing (Source: Photo by the authors).

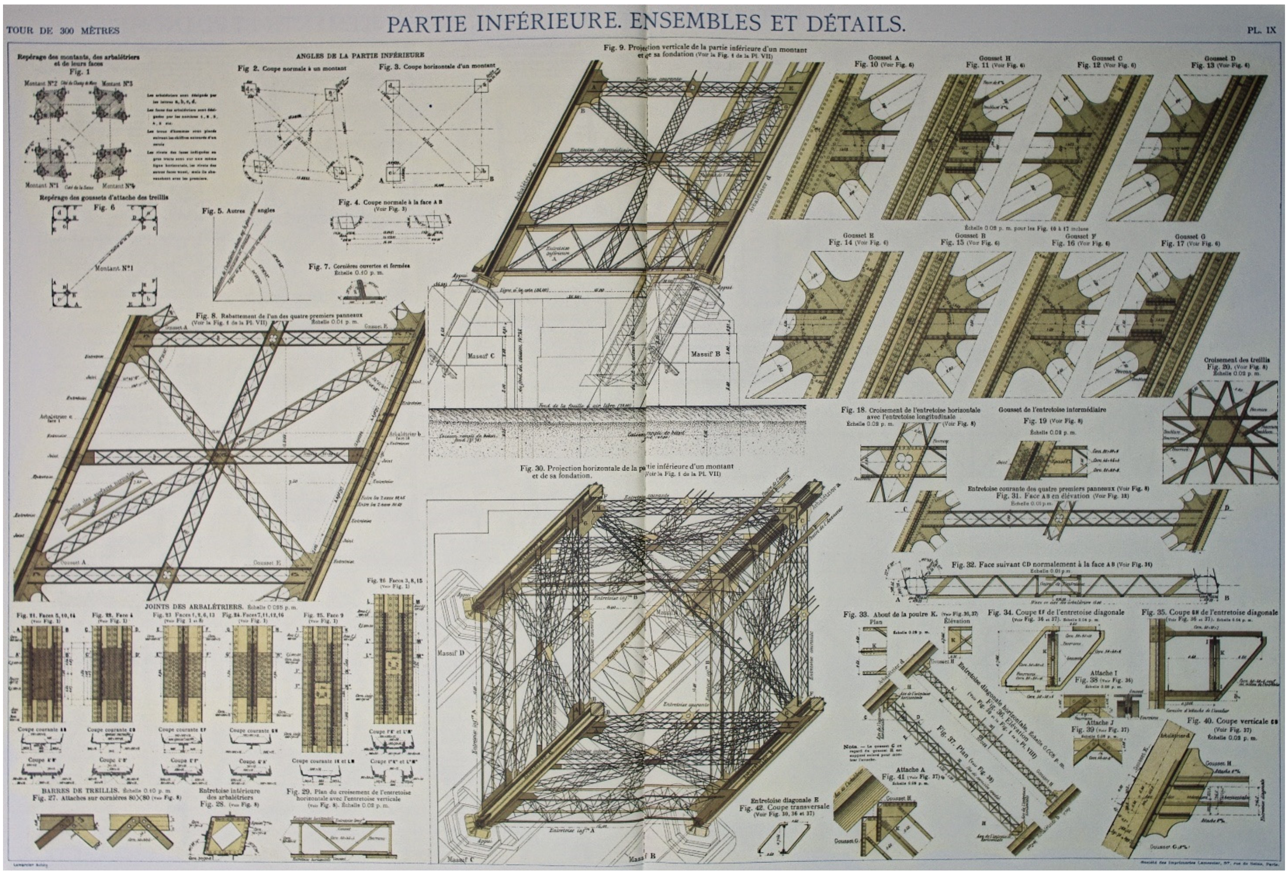

Fig. 2 Eiffel Tower: Details of joints (Source: Büro Gustave Eiffel).

transportable structures using a pattern of rods and nodes, substantiated by steel rods and point connections [18].

The connections resemble a human articulation and include a dynamic element, the spring, to modify the static behavior of the structure (Fig. 3). The geodesic sphere was also investigated by Fuller using the principle of tensegrity [19]. He made this type of structure famous, so much so that he proposed a patent for it [19]. Despite its complexity, the connection is potentially usable by all and requires only a few elements.

The examples provided (Table 1) illustrate the design and technological advancements applied to the issue of connecting different building components. The Japanese and Chinese techniques, Crystal Palace's solutions, and Buckminster Fuller's connection of the geodesic dome rods provide opportunities for direct comparison with the building. These examples represent the objects through which the building gains three-dimensionality. Japanese carpentry can be considered an early form of industrialization in the construction process. The range of techniques used to make structural and architectural joints was limited. This limited range allowed for easier construction and maintenance operations due to the high degree of flexibility in all the building's technological units. The goal of these examples was to take advantage of technological innovations, such as the use of metal, to create structures that could be quickly assembled, disassembled, and easily transported. In this case, we see a progressive trend towards favoring such operations, with a simplification of the elements that make up the connection and an increase in ease of repetition. This design aims to investigate the building's reversibility. The design phase is the moment when the designer analyzes the node, understanding its possible variations and its interaction with the rest of the structure. The node has a troublesome nature and is considered

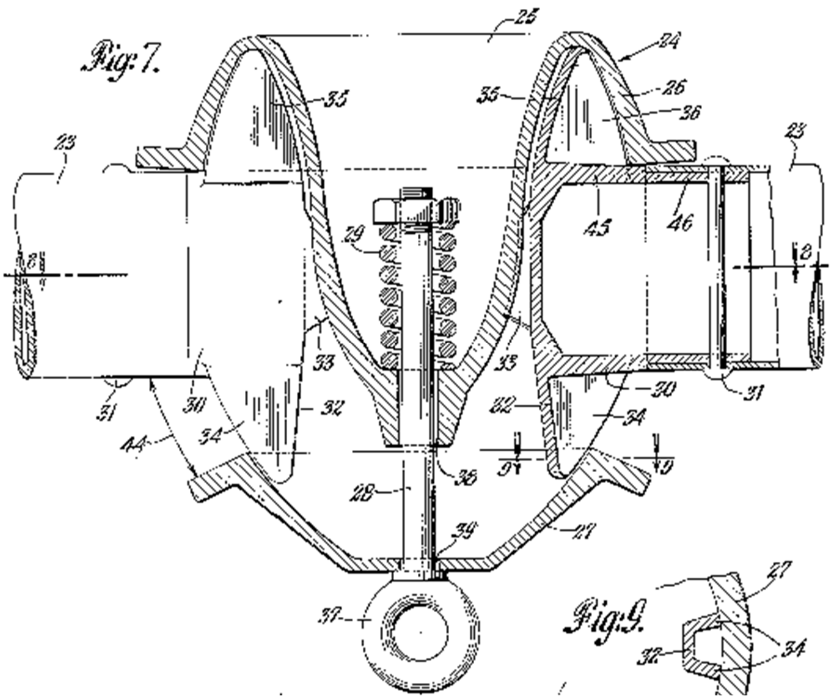

Fig. 3 Details of Buckminster Fuller's geodetic dome joints (Source: US Patent 2'682'235).

a potential weak point of the building. This issue must be resolved through technology and technique. In this context, it is worth mentioning the work of Italian architect Mario Ridolfi, who contributed to the development of the first "Manuale dell'Architetto" in 1946 [20].

Within the manual, Ridolfi used the tool of the abacus to categorize the main morphological variations of building elements according to specific parameters. Although the primary purpose of the abacuses is to provide standard, proven solutions, Ridolfi viewed the abacus as the result of reflection on the possible combinations of elements within the project [21]. Interestingly, mixing different standardized nodes within the abacus can lead to the creation of new elements. The same can occur with DfD—the combination of different technologies can lead to the emergence of new methods.

2.3 Case Studies

This section aims to present three case studies that demonstrate the use of dry construction techniques with various materials in different building layers. The methodology involves:

- Identifying projects constructed using dry technologies;
- Identifying disassemblable technological systems within each project;
- Analyzing the selected systems by studying each of its sub-assemblies and disassembling it to arrive at its minimum components, including the material used, reason for use, assembly method, and the possibility of reuse or recycling.

As indicated in Table 2, all the projects were completed within a 15-year time frame and precede the Paris Agreement (2015). However, they still offer interesting solutions that promote disassembly and flexibility. The three selected projects are:

(1) Centre Culturel Jean-Marie Tjibaou, built by Renzo Piano Building Workshop in 1998 in Nouméa, New aledonia.

(2) Auditorium del Parco, built by Renzo Piano Building Workshop in L'Aquila, Italy.

(3) A prototype self-built and demountable geodesic dome by the Italian firm "Architetture Precarie".

Table 1 Analysis of connection typologies within history.

Connection type	Material	Country	Period
Dougong	timber	China	Since 770 BC
Dovetail connection	timber	Japan/China/Europe	Since 12th century
Half lap connection	timber	Japan/China/Europe	Since 12th century
Tenon-mortse joint	timber	Japan/China/Europe	Since 12th century in China and Japan; since 15th-16th centuries in Europe
Crystal palace joint	cast-iron	Europe (England)	1851
Eiffel tower connection	iron	Europe (France)	1889
Geodesic dome ball-like joint	steel	USA	1949

Table 2 Classification of the case studies analysed in the research.

Project	Designer	Country	Year
Centre Culturel Jean-Marie Tjibaou	RBPW (Renzo Piano Building Workshop)	New Caledonia	1998
Self-built geodesic dome	Architetture Precarie	-	2011
Auditorium del Parco	RBPW	Italy	2013

The Centre Culturel Jean-Marie Tjibaou (Fig. 4, Table 3) is a public building spreading over an area of approximately eight hectares. The ten huts are a strong architectural feature of the complex and reflect the traditional design of Kanak huts, which they were inspired by. For this reason, the architect chose to use lightweight, primarily wooden technologies. Each hut is designed with a special system in front of the glass surface that serves both an architectural and thermal regulation function, promoting the chimney effect. The double skin (Fig. 4) is constructed entirely using dry systems. The main components of the system are rods made of two glulam ribs, one curved and one straight, which are held in place by horizontal struts. A steel plate is bolted to the end of both ribs to connect to the ground plate. The vertical rods are connected to each other by steel struts, similar to those used to support the ribs. The gaps between the rods are filled with panels made of a framework and wooden listels that also serve as brise soleil.

Table 3 Centre Tjibaou: Analysis of the double skin system.

Components	Part	Material	Reason	Assembly	Reuse	Recycle
Vertical Rod	Ribs	Gulam Iroko Timber	Little maintenance	Screwed	no	yes
	Ground Joint	Stainless steel	Durability, stiffness	Fixed to the ground by wet, and to the ribs by a device screwed technique	no	yes
	Horizontal bar	Stainless steel	Durability, stiffness	Screwed to the ribs	no	yes
	ties	Stainless steel cables	Durability, mechanic characteristics	Bolted to steel plates	no	yes
Louvres	Frame	Iroko timber	Little maintenance	screwed	yes	yes

Fig. 4 Left: View of the cultural centre (Source: Fondazione Renzo Piano); Right: Detail of the ground connection of the double skin façade (Source: graphic elaboration by the authors).

This system is technologically flexible, and the use of dry technologies and high prefabrication make disassembly operations easier. It is notable that the connection to the ground is clear and accessible. Declaring the structural function of the joint elevates it to an ornamental technological element. The second project analyzed is the Auditorium del Parco (Fig. 5, Table 4), also designed by the Renzo Piano Building Workshop. The project arose from the need to provide L'Aquila, a city in Abruzzo that was severely impacted by an earthquake in 2009, with a new Auditorium after the previous one became unusable. The structure is made entirely of wood, both for its resilience and this demountable solution is easy to inspect and mostly made from sustainable materials. In this case, the joint is not visible on the exterior; it remains hidden within the envelope.

The latest case study is a structure that can be disassembled and transported design by the Italian firm Architetture Precarie (Fig. 6, Table 5). It is a prototype geodesic dome created as part of a project focused on investigating self-construction and demountability in building design. The dome's canonical shape has been slightly altered to meet design needs, resulting in a dome with a base diameter of 3.50 m and a height of 2.90 m. Sustainability is a key focus of this project in terms of the environment, economics, and social impact. The prototype is made from completely reclaimed materials,

Table 4 Auditorium del Parco: Analysis of the envelope.

Components	Part	Material	Reason	Assembly	Reuse	Recycle
Structural system	Beam grid	Laminated Timber	Sustainability, elasticity	Nailed, screwed	no	yes
	Panels	Xlam	Prefabbrication, sustainability	Screwed	yes	yes
Skin	Bearing frame	Larch	Lightweight, sustainability	Screwed	no	yes
	Panels	OSB (Oriented Strand Board)	Lightweight, cost-effective	Screwed	no	no
	Sealing layer	Bitumen	Water resistant	Glued	no	no
	Insulation panels	Glass fiber	Thermal insulation	-	yes	yes
	Cladding	Larch	Sustainability, Lightweight, Easy to assembly	Screwed	no	yes

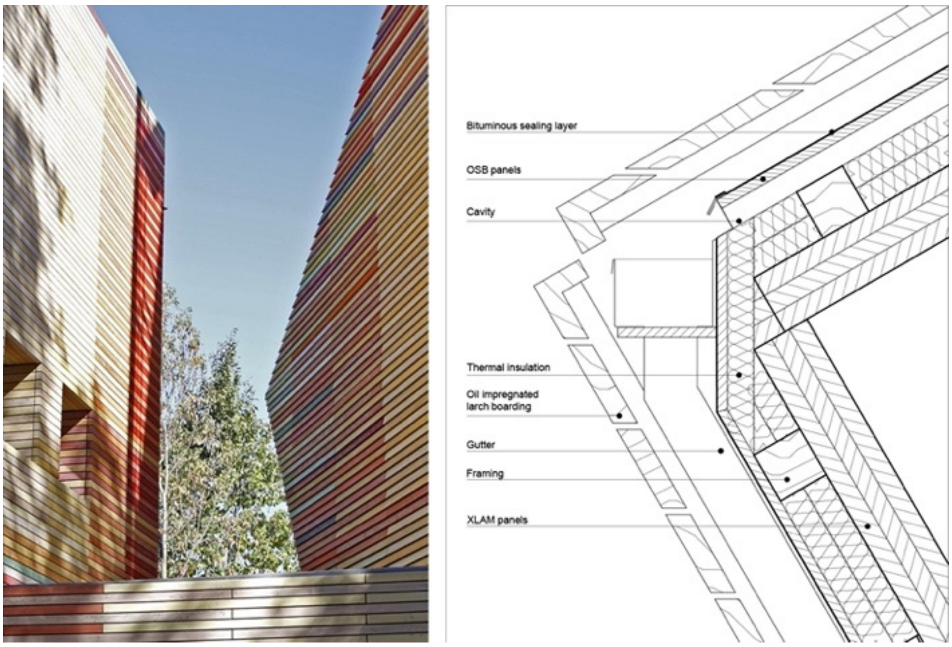

Fig. 5 Left: Perspective view of Auditorium del Parco (Source: Fondazione Renzo Piano); Right: Detail of the envelope (Source: graphic elaboration by the authors).

Table 5 Geodetic dome: Analysis of the structure.

Components	Part	Material	Reason	Assembly	Reuse	Recycle
Rods	Rod	Reused timber	Sustainability, Lightweight	Screwed	yes	yes
Joints	Ring-shaped joint	Reused Iron	Mechanical charachteristics	-	yes	yes

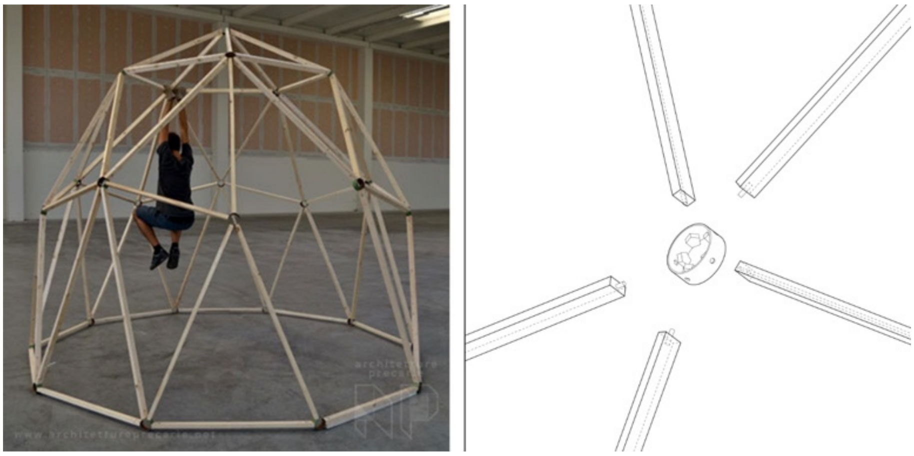

Fig. 6 Left: Geodesic dome prototype (Source: Architetture Precarie); Right: Axonometryc view of ball-shaped joint (Source: graphic elaboration by the authors).

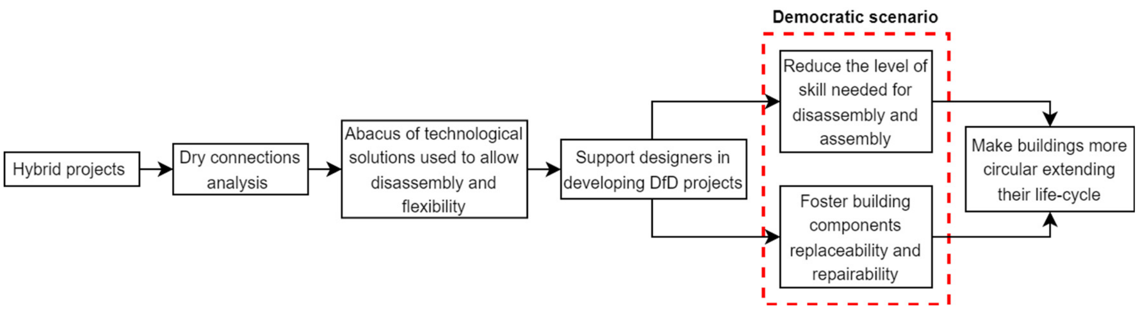

Fig. 7 Graphical representation of the results.

with the dome's struts made from transformed planks and the joints cut from iron pipe. The joint design is simple and aims to facilitate easy assembly and disassembly. Each ring-shaped joint can accommodate five rods attached by screws.

Although this is just a prototype, its low cost of fabrication and simple assembly process could make it a popular option, but its durability under frequent assembly and disassembly remains untested. The small number of components in the structure enhances its flexibility. Although only one of the submitted projects fully aligns with the DfD strategy, the other two RPBW projects show a focus on using dry, sustainable technologies. Based on Brand's model, the solutions presented in the case studies can be applied to both the structure and skin layers. The double skin system seen in Centre Jean-Marie Tjibaou can be applied to both layers, thanks to the use of dry construction techniques, the clear division of system components, and accessible joints. This concept is flexible and versatile, allowing for different shapes and materials. The envelope of the Auditorium is more similar to a traditional envelope, particularly in terms of mass and thickness. This type of system offers less flexibility because the skin layer and structure layer are strongly interconnected, potentially making disassembly more challenging. The geodetic dome concept could be used as either a structure or a skin, particularly for roofing. Its use as a structure may be more suitable for temporary structures that require large spaces and quick construction times.

3. Results and Discussions

The methodology used for analyzing the technology used in various systems has both a study function and a cataloging function. This methodology breaks down the different parts of a technological system to better understand it and to figure out how joints and systems work. Mario Ridolfi's work on abacuses in the Manuale dell'Architetto is a source of inspiration for this approach. Despite years of research, the DfD strategy has only been fully implemented in a few projects. Most projects only incorporate DfD in certain areas, with only a few utilizing the strategy in all building layers. Therefore, it is crucial to investigate hybrid projects that incorporate elements of DfD, not just those that fully embrace the philosophy. Another important result of the research is that we already have the knowledge to put in place DfD practices. The projects that have been shown in this paper demonstrate that there are many technologies to be applied in order to allow disassembly, but also to allow people with different skills to carry out self-build or maintenance operations. The analysis carried out allows also evaluating the effort and the ease to assembly and disassembly. Information about each analyzed system can be stored in an open database to provide designers with a useful tool to determine the best technology for disassembly, flexibility, and architectural design. This methodology has the potential to enrich current tools and lead to new solutions through material changes and different applications. Sharing this information is essential for the development of a circular economy in the construction industry. Currently available tools, such as the Circular Building Toolkit developed by Arup and the Ellen MacArthur Foundation, provide a description of the project, but lack technical details about the technology used. In Fig. 7 a flow chart is used to explain the results.

4. Conclusions

Since ancient times, joints have been deemed crucial in both the structural and architectural perspectives of building. Today, the need for sustainability in the building and construction sector has led to a focus on the DfD approach, which relies on dry connections and lightweight structures. In DfD, joints are deemed essential for disassembly. The strategy is validated by academics and researchers and has the potential to facilitate a transition from a linear to a circular economic model in the AEC sector. Despite the knowledge of DfD being widespread, its implementation remains limited, potentially due to a lack of knowledge about dry construction techniques, which DfD relies on. Wet construction techniques, which dominate the building sector, require less accuracy in design but dry techniques, often relying on prefabrication, demand greater precision. Since components produced in prefabrication are made off-site, correcting design issues during construction become more challenging.

It is important to emphasize the use of dry connections in order to facilitate the replacement and repair of building components. Achieving this could be a significant milestone towards creating a more democratic scenario in the building sector. This paper's proposed methodology aims to provide designers with a reference guide for incorporating the DfD strategy into their projects by gathering information on existing technological systems and serves as a tool for spreading knowledge gained by architects and engineers in projects where disassembly, flexibility, and architectural quality coexist.

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