Project Review

Multihalle Pavilion: The renovation of an innovative, experimental structure from the 1970s

Steffen Lehmann

This article discusses the significance and challenges of renovating a unique 1970s experimental timber building and iconic structure: the Multihalle Pavilion in Mannheim (Germany), which has the world's first and largest self-supporting wooden grid shell roof structure. Originally conceived as a temporary structure for the 1975 Federal Garden Exposition, Multihalle uses a lattice grid shell structure with gentle curves, remarkably slim profiles, and a translucent roof. The term 'grid shell' refers to a doubly curved surface formed from the lattice of timber with uniform spacing in two directions. Furthermore, this was one of the first buildings in Germany whose plan and drawings for components were designed using a computer system, well before the arrival of ubiquitous CAD programs. The purpose of the article is to widely disseminate knowledge about an innovative building and to provide an update on the project and its ongoing renovation efforts, as recently observed by the author during a site visit. The article first discusses the history and significance of the building, its unusual structural solutions, and explains the project's background. It then reports on the current state of the rescue initiative, the various renovation activities, and concludes with the outcome of a 2019 design competition, which called for new usage concepts to regenerate Multihalle; it produced sustainable and viable options for its redevelopment by conversion into a leisure, sports and cultural complex. A main conclusion is that the innovation and learning derived from the renovation of such an unusual structure are of immense relevance and importance for future projects. The renovation of this experimental building was not without risks and technical challenges, and the fund-raising took longer than initially expected; however, based on its influential contribution to 20th century architecture, it is also an important commitment to the preservation of our cultural heritage from the 1970s.

Keywords: *Grid shell structure; sustainable renovation; structural engineering innovation; temporary building; efficiency; architect-engineer Frei Otto; Mannheim, Germany*

1 Introduction

The Multihalle Pavilion is a large exhibition building located in the city of Mannheim, Germany. Designed from 1972 to 1974, Multihalle was first conceived as a temporary structure for the Federal Garden Show (the Bundesgartenschau, BUGA, a biennially held horticultural exhibition), which took place in Mannheim and opened in April 1975. For the host city, this prestigious event meant that an entire inner-city area was redeveloped with a new public park; this was an important factor in accelerating its postwar reconstruction process. During the garden show, this astonishing building was nicknamed 'Das Wunder von Mannheim' (the miracle of Mannheim). It was used as a temporary multi-purpose hall for exhibitions and events, with a popular café and restaurant. Its acclaim and technological significance led to a change of plan to make the building permanent. Based on its architectural relevance, engineering ingenuity and general popularity, the city authorities decided not to demolish the temporary complex at the end of the BUGA show, but to maintain the structure permanently.

The pavilion is a significant achievement in terms of its unusual shape, its striking double-curved roof and large structural span; furthermore, its innovative use of timber created a complex and flexible lattice structure, which was until then unrivalled in timber engineering. The creative planning process was also ingenious, and remains exemplary to this day.

The purpose of the article is to summarise the design and engineering work that went into the initial construction of Multihalle, in order to clarify the design philosophy behind this remarkable building and the process leading to the selected structural roof form. It also ails to provide an update on the ongoing renovation efforts, as observed by the author during a site visit in December 2023 (some of the following photos were taken during this visit) and discusses the risks and challenges of renovation an experimental building from the 1970s. In general, the comprehensive renovation project currently underway will make a significant contribution to the authentic preservation of experimental buildings from this era.

Multihalle is a multi-purpose hall (hence its name) embedded in a hilly site in Herzogenriedpark, a new public park that was created for the BUGA show. The pavilion was the result of a design competition in 1971, for which the firm Carlfried Mutschler & Partners of Mannheim created the winning design, in collaboration with landscape architect Heinz Eckebrecht. However, after the competition, the city and architects decided to revise their original scheme in favour of a tent-like structure. The decision was made to contact architect-engineer Frei Otto, who was known as an expert on lightweight tent roofs and tensile structures.

At this point, Otto had already achieved international recognition for his innovative roof structures, such as the West German pavilion for EXPO 67 in Montreal, and the large tent roof of the arena for the Munich Olympics in 1972. He advised the

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team on the possibility of a lightweight wooden grid shell that could be entirely prefabricated and would minimise the amount of material used. Frei Otto agreed to participate as a consulting engineer for the project. He introduced the term 'Holzgitterschale' (grid shell) to describe a grid of wooden slats that has a doubly curved, shell-like surface, formed from a lattice of solid timber laths bolted together at uniform spacing in two directions over an extended area.

In 1972, Otto and Mutschler started their collaboration, and designed the new building together with Mutschler's office partner Joachim Langner. It quickly became clear that the final pavilion design should have a free-form roof which would cover the three required separate spaces, with the main hall (called Multihalle) spanning an impressive 60 by 60 m area. Otto designed the innovative solution for the supporting structure as a wooden lattice shell, a regular mesh net of timber laths bent into the planned shape; which, to this day, remains the largest free-form wooden lattice shell construction in the world.

The construction technique of deforming a flat timber lattice mat into a three-dimensional architectural structure was unprecedented and had never been used at the scale of Multihalle's roof. This unique, eye-catching roof structure is widely regarded as groundbreaking, as it also represents the world's first wooden grid shell structure. Massive edge beams as glulam sections were used to hold the lattice in shape. While other wooden grid shells have recently been realised (mainly in the UK, Germany and Japan), none of them has a span that equals the pioneering Multihalle. Hence, this delicately curved building is still the largest self-supporting wooden lattice shell construction in the world.

The early 1970s were a period of change in society and in architecture. It is worth noting that the influential architects Le Corbusier (1887–1965) and Ludwig Mies van der Rohe (1886–1969) had both passed away earlier, and a younger generation had started to question their dominating legacy. As a critical reaction to the prevailing Bauhaus ideals and the exhausted modernist architecture of the late 20th century, there was a general trend towards designs that integrated technology, leading to the development of innovative construction materials, search for complete flexibility and new methods. Now, the central figures in postwar architecture included Louis Kahn, Peter and Alison Smithson, James Stirling, Aldo van Eyck, and Kenzo Tange; all of whom were influenced by the era's New Brutalism, and were involved in building large heavy-looking concrete structures. For example, in 1971, Louis Kahn was awarded the American Institute of Architects' Gold Medal; and Peter and Alison Smithson completed the Robin Hood Gardens housing project.

Frei Otto did not like the heaviness of Brutalism and preferred a much lighter architectural aesthetic. Lightweight building, with a concern for integrating sustainability within the designs, was still uncommon in those years. The Centre Pompidou, by Renzo Piano and Richard Rogers, was not completed until 1977. A strong influence had the unbuilt project 'Fun Palace' (1963-1973), a multi-functional complex designed by British architect and provocateur Cedric Price: the idea was that architecture should not be rigid and determine human behaviour but rather enable flexibility and possibility. 'Fun Palace' was a highly-influential, unrealised project conceived in the 'swinging London' of the early 1960s as a manifestation of a hyper-flexible playground and promoted as a new kind of cultural centre appropriate for modern life where the user could define the spaces and program. Frei Otto and Carlfried Mutschler were well aware of this project, the radical thinking that emerged from the Architectural Association School in London at this time, and the genre-bending work of Cedric Price, Archigram, Gordon Pask, Richard Buckminster-Fuller, and others. Similar to the ambition for Multihalle Mannheim, 'Fun Palace' was an unpredictable cultural launching pad and event space designed to be a constantly changing facility where visitors would be invited to assemble movable modular walls, platforms and floors, creating their own spaces for performances, production, exhibitions and educational courses of all kinds; all very similar to the ideas of Otto and Mutschler for Multihalle.

Post-World War II, most German cities were in ruins, and the country had lost a devastating conflict. However, by the early 1970s, Germany had a booming economy. The first oil crisis occurred at around this time, in October 1973, and it had a severe impact on industry, consumer confidence, and the naïve belief in infinite growth, which had hitherto generally prevailed. However, there was also a strong belief in the 'Wirtschaftswunder' (the economic miracle that seemingly drove rapid and unrestrained postwar reconstruction), and that innovation in engineering and technological progress would be able to solve any crisis. Still today, Multihalle embodies this optimism, confidence and aspiration of the time, and is considered a major postwar work of German organic architecture and structural engineering innovation (See Figures 1 to 5).

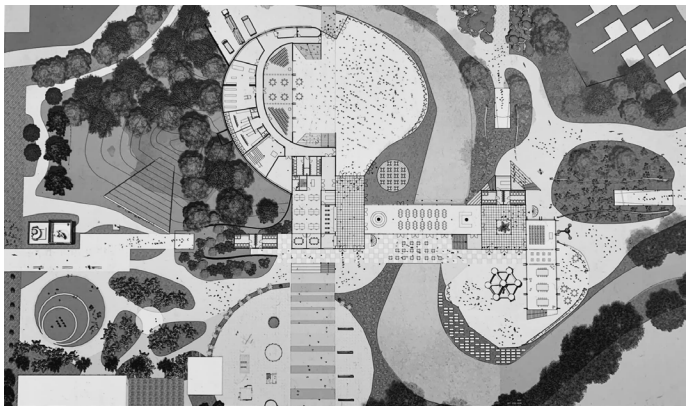


Figure 1: Plan of Multihalle situated in the park, with the two entry ramps from two sides, and the flow of space from one hall to the other. Multihalle is made of two fluidly connected grid shell domes that develop organically from the amorphous ground plan; 1974-75 (Images by Carlfried Mutschler).

Mannheim is the second-largest city in the German state of Baden-Wuerttemberg, after Stuttgart, the state capital; as of 2023, its population is around 320,000 inhabitants. The city is the cultural and economic centre of the Rhine-Neckar Metropolitan Region. This is Germany's seventh-largest urban region, with nearly 2.4 million inhabitants and over 900,000 employees. Mannheim's urban pattern is unusual among German cities in that its city centre streets and avenues were laid out in a square grid pattern – leading to the city's nickname 'Quadratestadt' (Square City). Before World War II, Mannheim was a centre of industrial innovation. For example, in 1886, it was here that the

inventor Carl Benz developed the first automobile, patented the first gas-powered automobile, and drove it on the streets of the city. Therefore, the city's character and heritage made it the ideal location for the pioneering Multihalle that was equally innovative but breaking with the block tradition.

The renovation of Multihalle is not as straight forward as it might seem in hindsight. How to deal with the sometimes-controversial architectural heritage of the 1960s and 1970s is a question that historical preservation experts have been struggling with for a long time. In recent years (in 2011), there had been increasing damages from water ingress to the Multihalle, and it became critical to repair the ageing grid shell to ensure its long-term survival. The originally designed structure was meant to be only temporary, like a nomad's tent. Hence, simply extending the longevity of an experimental building, which was never planned as a permanent structure, creates multiple challenges and risks; these are subject of the second part of this article. At the moment of writing, the entire complex is under complete renovation, following the development of a new usage concept.

Today, the future of Multihalle looks positive again, as the city of Mannheim is working with a dedicated group of architects, artists, engineers, local residents, companies and universities, on a sustainable concept to ensure the structure's revitalisation and long-term preservation.

2 A pioneering building that was designed with extraordinary ambition

2.1 Multihalle: a multifunctional exhibition hall with an unusual roof

Multihalle is composed of two fluidly interconnected large main spaces underneath grid shell domes that develop organically from an amorphous ground plan. Tube-like walkways and stairs lead to the core, and the impressive dimensions of its spaces can be experienced when entering the main hall. The grid shell roof establishes a spatial flow and visually connects the three different spaces of the building. The entire complex was carefully integrated within the artificial topography and hills of the new parkland, creating a continuation of the park landscape with architectural means. The designers' immediate idea was to create a lightweight, airy structure that was in harmony with the park's landscape (see Figures 1 and 2). The wooden shell roof has no right angles and nestles into the park landscape in a biomorphic way, evoking naturally occurring forms such as a hill or an organism with body parts. The architectural concept of 1972 stipulated that the complex should visually merge with the topography of the hills, undulating landscape and artificial watercourses; the way to achieve this – the architects thought – was to make Multihalle's grid shell look like two artificial hills or two large umbrellas (Happold and Liddell, 1975).

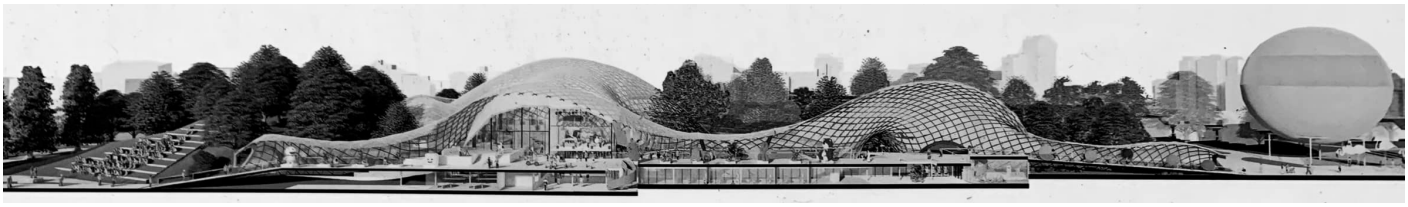
The hope was also that the lightweight structure would reduce the overall cost of the project, and keep it within the limited budget of only 6 million DM (Deutsche Mark, the West German currency at the time).

In contrast to the soft and amorphous landscape stands the precise and modular structural system of the grid shell. The soft-shaped roof's support structure spans up to 85 metres (280 feet); it is made of a double-layer mesh of solid wooden laths (roof battens) with a 50 by 50 mm (2" x 2") cross section, at 0.5 m intervals. The double curvature of the design gives the membrane strength and stiffness, but with four layers of wooden laths to be joined, the connection system is complex. The shell is braced with stiff bolt connections, as well as a cable net arranged diagonally to the grid shell fields. Twin cables with 6 mm diameter are used for bracing; they are connected at every sixth node, to increase the diagonal stiffness. The grid of laths acts in compression to efficiently carry the vertical loads. At the ends of the hemlock laths, connected glulam (glue-laminated timber) beams brace the laths of the grid shell. Where the mesh meets the ground, there are four different edge details (boundary types): arches, concrete, glulam timber beams, and cable boundaries. The selected roofing is a thin, watertight translucent PVC membrane covering the entire shell; it is 30 per cent light permeable, so that the interior is suffused by a soft, evenly diffused light.

The Multihalle Pavilion attracted worldwide attention at the time of its construction and opening, as an architecturally outstanding, pioneering milestone in several engineering disciplines. The chosen grid shell roof required close coordination, detailed planning and engineering, due to the complexity of its structural system. Optimising the roof form in terms of structural engineering was a matter of painstaking trial and error – using hanging models made of chains and nets, which, when turned upside down, generated 'ideal' filigree grid shells made exclusively of pressure-loaded laths. The design of Multihalle's roof structure stemmed from Otto's research conducted on grid shells over the previous years at his Institute for Lightweight Structures at the University of Stuttgart. A collaborative team of structural engineers around Frei Otto, based in Stuttgart, and at Arup in London, calculated the specifications of the innovative wooden structure (Otto, 1972; Baecher and Otto, 1978; Liddell, Williams and Rogers, 2017).

2.2 The development of Otto's form-finding methods

In the late 1950s, Otto had become interested in lightweight shells, which could be formed using the *Hookean Principle* of inverting a hanging net (named after inventor and architect Robert Hooke, who used the same method in 1670 to show Christopher Wren how the double-vaulted dome of St Paul's Cathedral might work). Using physical models, such as an upside-down hanging chain model, for the form-finding process of the structure and



definition of the final shape was a well-known method, which had previously also been applied by Barcelona architect Antonio Gaudi in the 1890s. It allowed Gaudi to visualise the asymmetrical catenary arches for his experimental structures, such as his churches Colònia Güell or La Sagrada Familia, and to design more fluid spaces that would fit any free-form plan.

Figure 3: Historical images of Multihalle with one of the entry ramps and the view from above, 1975.

For the Multihalle's design process, Otto also used physical form-finding models to define its shape. Long before the rise of nonlinearity and curvilinearity in architecture enabled through computer-based parametric design, this simple yet effective method of upside-down hanging models allowed engineers to assess and calculate irregular structures. A hanging chain model is based on the reverse principle: the shape of the hanging net corresponds to the ideal shape of an upright structure.

Figure 4: The Multihalle Pavillion, 1974

The models were effective in creating pure tension shapes which, when inverted, created ideal pure compression shell results. Frei Otto had previously used this technique to derive his first timber grid shell for the DEUBAU German Building Exhibition in Essen (Germany) in 1962, by suspending threads loaded with nails. In the same year, Otto built, with some students at UC Berkeley (USA), a temporary trial structure of a dome standing on four points, using steel rods (in the 1970s, several architecture schools would repeat similar design and construction experiments). Later in 1962, Otto built the experimental timber structure in Essen on a 15 by 15 m elliptical plan (Liddell, 2015 and 2021).

This was Otto's first real engineered grid shell – also a temporary structure, constructed for DEUBAU. Subsequently, his two lath domes for the West German pavilion at the 1967 World Expo in Montreal also applied grid shell principles. Two small auditoria were required within the Montreal Expo tent; these were made using grid shell construction. The meshes were prefabricated in Germany and sent to Canada folded into bundles, where they were opened up and installed on site. The grids were clad with thin plywood sheets to form the soft-shaped enclosures. This series of grid shell studies subsequently led to the publication of "IL10" – a report by the IL-Institute, devoted solely to the grid shell typology (Nerdinger, 2005; Stahl and Rosenkranz, 2016).

For Multihalle, Otto further refined the technique of using rope net and hanging chain models. The large hanging model at 1:100 scale was then measured using stereo-photogrammetry; computers were used in parallel to check the balance of forces in the structure numerically, to determine the coordinates for the individual nodes. Using the scale models, it was possible to test the structural calculations with a computer program for non-linear frameworks. In the mid-1970s, this was an application of cutting-edge, novel methods. With a roof area of over 9,500 m2 (100,000 sq ft) and spans of up to 60 metres (200 ft), this unique timber lattice roof structure remains the largest self-supporting timber grid shell structure in the world; indeed, in 1998, it was listed as a historical cultural monument.

2.3 A close collaboration between engineer and architect

In 1975, the Bundesgartenschau (BUGA, the federal horticulture show) was celebrated in Mannheim's two public parks, Luisenpark and Herzogenriedpark. A number of pieces of infrastructure were developed for the show, as well as the groundbreaking Multihalle.

After the decision was made in January 1970 to hold the 1975 Federal Garden Show in Mannheim, two design competitions were announced, in which architects and landscape architects were supposed to present their ideas for the two park sites. The design competition for Herzogenriedpark called for a large, covered meeting point for various activities, and a café with a seating terrace by the water, as the central area.

In 1971, the firm Carlfried Mutschler & Partners collaborated in the design competition with garden architect Heinz Eckebrecht; they emerged as winner for the overall planning of the section of the Herzogenriedpark where today's Multihalle is located. Originally, Mutschler had planned a temporary event space covered by disc-like roof elements attached to oversized balloons, creating a column-free space. The meeting point was covered with large umbrellas that should be hung from gas balloons.

However, although this was technically possible, it did not comply with building codes. A wide variety of types of pneumatic constructions were examined, but these would have incurred high costs; hence, various tent constructions were discussed. This was when the work by Frei Otto on grid shells came into the discussion. After they had to reject the idea of the floating roof landscape, Muschler brought in Frei Otto to help him. This is not an unusual approach, and many of these architects' buildings were created through collaborations. Soon after, a collaborative team was assembled as a group of equals.

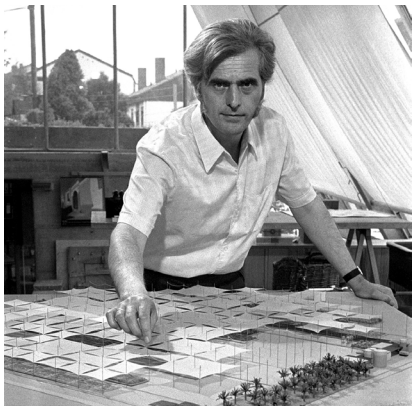
Figures 5: Winning proposal of the ideas competition for the revitalisation and usage concept of Multihalle, by COFO Architects and PEÑA Architects, 2021. The renderings of the new usage concept by show the spatial organisation, which is aligned with four main catalysts: tent/square, platform/stand, plate/atrium, and roof/stage. The architects proposed only minimal interventions that would not change the roof structure (Courtesy COFO Architects, Guillem Colomer).

The starting point for the grid shell was Frei Otto's first rough wire model of the preliminary design. In this 1:500 model, however, the final shape could only be approximately specified. The perceived advantage of a grid shell as a roof structure was that it is only subjected to compression and not to bending under its own weight. At the same time, the locations of the various functions were determined; visitors were to be led into the hall on two levels, and the idea of a raised walkway emerged.

Carlfried Mutschler (1925–1999) was a German architect based in Mannheim; he realised complex large-scale buildings for the private and public sectors. From 1978, he taught as professor at the Städelschule in Frankfurt am Main. His early work was influenced by his studies with Egon Eiermann at the university in Karlsruhe, with characteristic features such as clear rectangular lines and exposed concrete.

A turning point in the development of Mutschler's understanding of architecture was the *Darmstadt Conversations* symposium of 1951, where he met Hans Scharoun and Hugo Haering, and he was impressed by their expressionist buildings. In collaboration with Frei Otto, he designed Multihalle for the 1975 Federal Garden Exhibition (BUGA) in Mannheim's Herzogenriedpark. Both men were born in the same year (Langner, 1984).

Frei Otto (1925–2015) is one of the most internationally renowned and innovative architects of the second half of the 20th century, and is a central figure in German architecture. He was a revolutionary architect and structural engineer noted for his use of lightweight structures – in particular, tensile, membrane structures, tents and grid shells; including the famous roof structure of the Olympic Stadium in Munich, for the 1972 Summer Olympics. Otto started experimenting with tent structures around 1945, and established his private practice in Stuttgart in 1952.



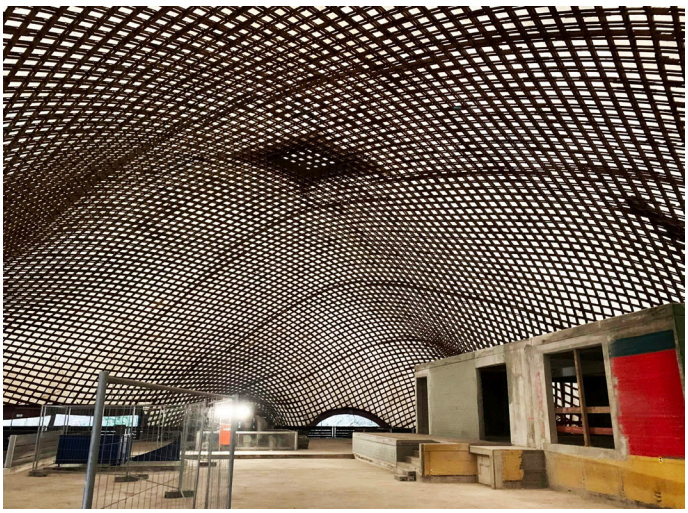
He earned a doctorate in tensile constructions at the Technical University of Berlin in 1954 (his doctorate thesis plus other work was published in 1962 and 1966 as *Tensile Structures Vols. 1 & 2* and translated into English, published by MIT in 1967). His saddle-shaped cable-net music pavilion at the Bundesgartenschau (Federal Garden Exhibition) in Kassel in 1955 brought Otto his first significant attention. He specialised in lightweight tensile and membrane structures, and pioneered advances in structural mathematics and civil engineering. In 1958, Otto taught at Washington University in St. Louis, where he met Buckminster Fuller. Representative of organic architecture, Otto's structures

were inspired by natural phenomena and biology, such as spider webs, leaf structures and soap bubbles.

Otto founded the interdisciplinary Institute for Lightweight Structures (ILS) at the University of Stuttgart in 1964, and headed the research institute until his retirement as full university professor (in 1991); he led the institute over 27 years to achieve worldwide recognition. The types of structure with which Otto was mainly concerned included membranes, nets, suspended structures, grid shells/compression shells, and pneumatic structures. He explored how to create spaces with the minimum of materials and effort. Besides the Multihalle Pavilion, major works include the West German Pavilion at the Montreal Expo in 1967, and the tent roof of the arena for the 1972 Munich Olympics; they were all celebrated for their grace and originality (Otto, 1971 and 1976).

When Otto was invited to join the design team for Multihalle, he already had previous experiences with grid shells, such as the projects in Essen and Montreal, although these were on a much smaller scale. Georg Vrachliotis noted (2016 and 2018) that “Frei Otto saw his structural models as cultural indicators whose meaning often went beyond the purely physical feel of the individual object and had to be read as experimental symbols for an open society. Multihalle embodies this like no other building of the 20th century.” In the TV documentary *Von Seifenblasen und Zelten* in 2005, Otto mentioned that he considered the Multihalle Pavilion to be his “boldest building, much bolder than the Olympic roof”. Using wood as a multi-curved roof structure was a risk, and without precedent in architectural history.

In 1982, Otto was awarded the Grosser BDA Preis; 2005 the RIBA Gold Medal; and in 2015 the Pritzker Architecture Prize, shortly before his death. Until 2015, Otto remained active as an architect, engineer and consultant to numerous projects in the Middle East. One of his more recent projects was his collaboration with Shigeru Ban on the Japanese Pavilion at Hannover EXPO 2000, a grid shell structure made entirely of paper tubes (Roland, 1965; Drew, 1976; Otto and Rasch, 1996; Nerdinger, 2005; Info-Dienst Holz, 2015; Meissner and Moeller, 2015; Vrachliotis, 2016).



As in the case of Multihalle, he was often approached to form part of a team to tackle complex structural and architectural challenges. Frei Otto’s visionary ideas, generous collaborative spirit and inquiring mind have influenced countless others throughout the world.

2.4 Frei Otto’s earlier structural experiments with lightweight grid shells

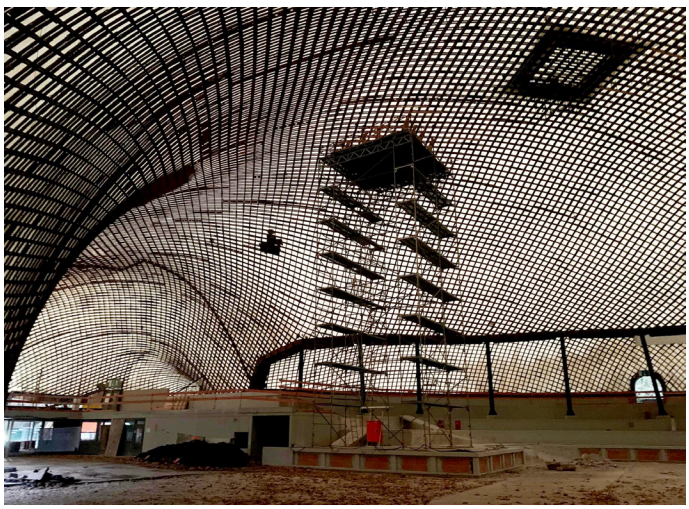
At the 1962 DEUBAU building exhibition in Essen, Otto created his first wooden slatted grid shell dome. It had an area of only 230 m2 (2,475 sq ft) laid out on the floor, and consisted of thin 40 by 20 mm slats folded in a square. A mobile crane lifted the slatted frame 5 m high in the middle. The previously loosely connected slats now crossed each other in a diamond shape. Otto had the ends of the slats attached to a surrounding support, and only then could the screw bolts be tightened on the connections between the wooden strips. The finished supporting structure is similar to that of a Zollinger roof (a vaulted roof structure invented by Friedrich Zollinger around 1921), but is made up of 1 to 2.5 m short wooden strips (lamellas) which do not cross over in the middle.

The erection of the DEUBAU grid shell is described in the literature:

> *The slats were laid out in a square grid on the floor and loosely connected at the crossing points. A mobile crane pulled the middle of the grid 5 m up. The slats curved, the edge panels warped in a diamond shape. A curved dome was created from the flat grid. The ends of the slats were then attached to a support ring, and the bolt nuts in the junction points were tightened for stiffening. The shape was stable and the dome was load bearing. (Memo on the DEUBAU 1962 grid shell, dated October 2017)*

Otto built a second grid shell in 1966–67: this time, a double-arched, wooden lattice shell inside the West German cable-net tent pavilion, as a lecture hall and foyer during the Expo 67 International and Universal Exposition in Montreal (Maushake, 1967). The project was built ahead of time in Germany, and then constructed on site in a short period. The pavilion was noted for its grace and originality, and is an early example of the tent structures that Otto later became known for.

The Montreal grid shell roof had been erected already in August 1966. A curiosity here is the fact that a wooden structure, prefabricated in Stuttgart, was brought to wood-rich Canada. However, the preparatory work carried out in Germany beforehand bore fruit: the erection of the wooden domed roof construction went smoothly.



Many of the ideas from the Montreal grid shell were reapplied at Multihalle – for example, the use of two layers of continuous slats lying transversely to each other at intervals of 50/50 cm, placed on top of each other; and the use of hemlock wood.

In the same year, in 1967, Frei Otto completed the roof for the Institute for Lightweight Structures at the University of Stuttgart, where he held a teaching position. The Expo 67 structure from Montreal was re-erected at Stuttgart University, and houses the institute he founded in 1964. The structure is located on the university's Vaihingen campus and is listed as a historic monument. The building was renovated in 1993. In 1972, Frei Otto and Guether Behnisch designed the groundbreaking tent roofs of the arena for the Munich Summer Olympics in collaboration. The tent-like roof not only covers the main grandstand of the Olympic Stadium, but also spreads over the Olympic Hall, the Olympic Pool, and the paths connecting the buildings. As a result, the curved tent roof harmoniously blends in with the surrounding rolling landscape of the Olympic Park.

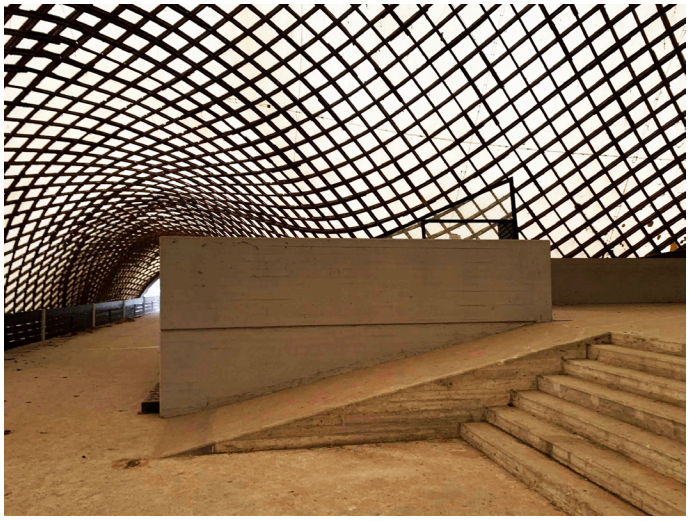
Until today, Multihalle has unjustly failed to receive the same appreciation as the Olympic roofs in Munich. In fact, Multihalle functions without complex foundations and supports, which Frei Otto had repeatedly criticised in the Munich tent structures.

In their essay "Der Weg zum Leichtbau", Kleinmanns and Kunz (2017) describe Frei Otto's early work and compare the various innovative structural systems he was able to develop. These successfully completed experimental structures gave Frei Otto the confidence to take his ideas to the next level with the monumental wooden lattice structure for Multihalle. Much later, Frei Otto commented that, from a technical point of view, the design of Multihalle was one of the most difficult tasks in his career (2005).

2.5 The grid shell as a structural system creates efficiency in form and material

Multihalle is a hall with a multi-curved grid. Even today, the grid shell of the pavilion enchants us with its lightness, transparency and unusually soft shape. The lightness of the structure lies in the combination of free form and constructive efficiency. The structural typology of the grid shell belongs to the family of hanging shapes. It carries loads that are evenly distributed along its axis via pure compressive stress, and this principle can be transferred to surfaces. The shape of the grid shell was found in Frei Otto's large wire-mesh model, which consisted of a flexible net, formed from hooks and rings; when spread out in the plane, it had square meshes. The form of the hanging model, optimised according to the form-finding process and architectural and construction requirements was then converted into a digital model and construction drawings (Liddell, 2021). The assembly of the monumental wooden lattice shell began in 1974. The network of the model was formed from solid wooden slats of hemlock pine measuring 50 x 50 mm. On the construction site, the slats were laid crosswise in two or four layers on top of each other, and connected with bolts to form a grid with twistable nodes and a mesh width of 50 cm.

In order to further develop details of the grid construction, several models were built in 1974 on a scale of 1:5; parts of the construction were even built on a 1:1 scale. The largest of the models had an area of 80 m2; this was used at the construction company to test the laying of the roof covering and to instruct the builders.



Multihalle consists of two shells that are connected by covered walkways. The actual event hall, as well as an expanded area with passageways and the restaurant, are located under the common roof made of two domes that merge into one another. The entire structure measures 160 by 115 m. The dome's highest point is 20 m above the floor. Its maximum transverse span is 60 m, and in the longitudinal direction, it spans up to 85 m (for more information on the size and structure, please see the Fact Sheet at the end of this article). However, when were grid shells invented? And how exactly do they work? Russian engineer Vladimir Shukhov, for an exhibition pavilion of the Russian Industrial and Art Exhibition, pioneered grid shell structures in 1896. Shukhov's earliest grid shell structure in iron was built in 1896 in Nizhny Novgorod, Russia. Since 1939, structures pioneer Pier Luigi Nervi (1891–1979) contributed to the development of structural forms of expression through reinforced concrete construction; he designed the diagonal lattice rib vault by crossing each arch, resulting in a structure with a mesh-like network (Nervi, 1966). However, Nervi's interest in expressing structural form with concrete was different from Otto's wooden grid shells.

Seventy years after Shukhov, Frei Otto reintroduced this forgotten structural system and popularised it. A grid shell is a structure which derives its strength from its double curvature (similar to how a fabric structure derives strength), and is constructed of a grid or lattice. According to Ted Happold, the term 'grid shell' refers to a doubly curved surface formed from a lattice of timber laths bolted together at uniform spacing in two directions (Happold and Liddell, 1975). This grid can be made of any material, but is most often wood or steel. In future, alternative lightweight materials could be trialled and explored to offer a weatherproof and durable solution.

Much of the complexity of grid shells concerns their construction feasibility and process of erection (Burkhardt, Hennicke and Otto, 1974; Schaur, 2005). Initially laying out the main lath members flat on the floor in a regular square or rectangular lattice, and subsequently deforming this into the desired doubly curved form that commonly construct large-span timber grid shells. This can

be achieved by raising the members from the ground, as was the case in Multihalle. During its erection, the grid is usually pushed up from below using scaffolding towers; and after the mesh is lifted into shape, the boundaries are fixed to increase the stiffness of the shell. More recent projects, such as the Savill Garden grid shell (2006), were constructed in a different way, by laying the laths on top of a sizeable temporary scaffolding structure, which is removed in phases to let the laths settle into the desired curvature.

A grid shell is highly responsive to gravitational forces, and results in structures that embody and express the logic of their force transfers. The tectonics of a grid shell as a support matrix on a bigger scale can easily be understood as a form of 'force fingerprint' (Tang, 2012; Chilton and Tang, 2016). There are also limitations of timber grid shells. In terms of construction feasibility, it needs to be considered that the softer the flat unstiffened grid is, the larger the number of support points needed during the erection of the grid. In addition, in the case of Multihalle, there was the challenge of durability, and the wooden structure soon suffered deterioration from moisture. Structurally, the weakest points of a grid shell structure can be observed in the regions of contraflexion, meaning the areas where a change of geometry occurs – specifically, when the shell changes from anticlasticity to synclasticity, which is usually the area that demonstrates most deflection. Additional stiffening is often needed for these regions.

Another typical challenge of grid shells was mentioned earlier: the installation and erection process on site, which relies heavily on effective teamwork and the careful layout and manoeuvring of the large fragile timber mat, which is susceptible to fracturing prior to gaining stiffness before deformation. This naturally limits how large the grid mat can be. The assembly process is very time-consuming, as it usually involves scaffolding tower structures to manually erect the shell from below into the correct shape. Although pneumatic erection or a PERI scaffolding system could be successfully used to lower the mat into shape safely over a sustained period, these methods may negate the scaffolding-free benefits of the 'push-up' system. (Herzog et al., 2004; Tang, 2012)

The erection of the wooden grid of Multihalle was correspondingly difficult. The shells were gradually shaped on site, attached to the edges, and adjusted and covered with the polyester grid fabric. Using forklifts and scaffolding towers, construction workers carefully lifted the roof into its final position. Once the roof structure was finished, the stability calculations were verified with static load check. On 30 January 1975, at the request of test engineer Fritz Wenzel, a load test was carried out in which 200 barrels of water were hung on the slatted grid. The shell gave way by only 79 millimetres, one millimetre less than had been calculated (Wenzel, 2018). After the successful load tests, Multihalle was opened to the public on schedule in April 1975, and the building gained an enthusiastic reception during the garden exposition.

3 The renovation and redevelopment of a modern milestone building

3.1 Multihalle:A sustainable building is one that already exists

Based on embodied energy and avoidance of construction waste, the most sustainable way to build is to adaptively reuse existing structures (Lehmann, 2010 and 2019). In architecture, adaptive reuse refers to giving buildings a new life and repurposing an existing structure for new use. Adaptive reuse of buildings can be an attractive alternative to new construction, in terms of sustainability, embodied carbon reduction, demolition waste avoidance, and social and cultural benefits (such as heritage preservation, maintaining memories). Renovating an existing structure and using an adaptive reuse model prolongs a building's cradle-to-grave lifespan, by retaining most of the building system, including the structure, the shell, and even some of the interior materials. However, it can also entail significant complexities and uncertainties, including issues of structural integrity, compliance with building code regulations, and potentially high costs.

The renovation of a modern building that was never meant to be a permanent structure adds an additional aspect, and can pose numerous challenges. Much of the durability of a timber building depends on the care given to its technical detailing, to keep the structural components dry, and on its moisture control. Hence, one of the questions in the project was how to adapt and renovate an innovative building of historical significance for tomorrow's needs?

The modern movement in architecture embodies an innovation in building materials, technology and theory, which began in the late 19th century and is still progressing today. The 1970s included new approaches to construction that have evolved over the decades and fundamentally changed the way we understand our built environment today. Preservation, renovations and restorations of the original pioneering works can range from authentic, almost wholly original 'time capsules', to entirely new interpretations of buildings that maintain only some of the original structure. This means that renovations can be more or less respectful. For instance, experimental structures and their overall spatial concepts must be viewed as an organic, holistic whole, in a way that is not necessary for other buildings.

In 2024, the Multihalle Pavilion turns 50 years old. Unfortunately, the building has been allowed to deteriorate, and its current redevelopment represents a direction rather than an endpoint. Once it is reopened to the public, a new usage concept will have to be implemented that ensures its long-term viability.

There are also unique technical challenges specific to

renovating a 50-year old, ageing experimental timber structure, to meet today's standards and tomorrow's purposes. It was clear to the City of Mannheim (the owner of Multihalle) that the initiative to preserve one of the world's most endangered architecturally important structures would not be a small challenge. The task requires a contractor who brings a wealth of prior experience to the job; with the analytical tools to understand how best to tackle the challenges. For example, the requirements of today's building code, expectations of sustainability, and the integration of services, are all very different from 50 years ago; and these concerns directly affect the remodelling of Multihalle.

Many of the historic finishes and fixtures will need to be preserved and reused, and the outcome will be a thoroughly renovated structure that retains its unique features. Once redeveloped, Mutihalle will meet the efficiency, security, sustainability (e.g., low embodied energy), and functionality requirements of the 21st century, while at the same time preserving the unique architectural character of the building, and restoring its original appearance.

3.2 The current state of Multihalle's awakening process

The renovation of Multihalle has been planned in three steps:

- First, a trial phase to determine the necessary works (completed, 2021–2024);
- In a second phase, the complete renovation of the complex (to be completed by 2027); and finally,
- The adaption of the interior architecture to a new usage concept (to be completed in 2028).

As a temporary structure, Multihalle was not designed to last forever; however, due to its popularity and the unique shape and construction, it was not dismantled as initially planned, but preserved. Overall, it is remarkable how well Multihalle has withstood the test of time for over 50 years. Nevertheless, in order to preserve and redevelop a building of this size, an extensive renovation became necessary. The lifespan of the timber had been exceeded, wooden components were attacked by moisture, and the supporting structure was partially deformed. The original roof coating was heavily damaged by UV light, and cracks in the membrane let water in. It became necessary to renovate the entire structure, and completion of this renovation phase is now expected by 2027.

Plans for a complete renovation of Multihalle were under consideration for several years; however, there was no funding available. Rightly, the City of Mannheim expected significant costs for the renovation; hence, it took many small steps until this project could go ahead. Securing all the funding required for a complete renovation was not easy, and took until July 2019.

In 1981, it became necessary to cover the hall with a newly developed plastic sealing membrane; this made the previously semi-transparent roof shell white. By 2011, this membrane had become porous, and water penetration damaged the wood of the roof structure and impaired its load-bearing capacity; consequently, the building was closed to the public. In addition, the wooden structure had shifted and deformed, albeit only minimally. In order to prevent further deformation, in 2008 a support tower was built in the centre of the large hall, for structural reasons. During the following years, the structural condition continued to deteriorate.

A preliminary cost estimate in 2012 by the city ended at around 5 million euros. In 2014, engineering office Fast + Epp was commissioned to develop a concept for renovating the building. In May 2016, a detailed cost estimate was commissioned, which calculated the conservation works at 3.39 million euros and the additional general renovation works at 11.6 million; this meant that a total of 15 million euros had to be found, to rescue the building. On the other hand, the cost of demolition was estimated at 1.02 million euros. One argument against the demolition was Multihalle's status as a listed "cultural monument of particular importance" (Ragge, 2019). Following a lengthy debate, in June 2016, the city council approved the demolition, unless a significant amount of money was raised by the end of 2017 for renovation, through external grants, sponsorship or crowdfunding. The building was in dire need of renovation, had been dormant for several years, and unless money came from private sources, the building was scheduled to be demolished in 2018.

It did not take much for a unique architectural work to be almost demolished, and the turning point came just in time in 2018. There was a change in attitude, and suddenly the City Hall stated that it had a "moral and historical obligation" to preserve Frei Otto's work. The deadline to find the funding was extended until the end of 2019. It was also recognised that Multihalle could be a perfect place for festivals, markets, cooking shows, or a cold-air hall for sports, as it offered shade in the summer, was not too windy in the winter, and was always covered. New flexible usage concepts evolved, from beach volleyball tournaments to other trend sports and closer cooperation with local schools, and it became obvious that there were many possibilities and almost anything could be accommodated.

A series of rescue initiatives followed to develop a funding strategy and secure the required funds. In October 2016, the Baden-Württemberg Chamber of Architects and the City of Mannheim together founded a support organisation, the Verein Multihalle e.V., an association dedicated to preserving the building. It aimed to promote its redevelopment, find partners and investors, and raise the necessary third-party funds. This association organises workshops on-site to explain its uniqueness and significance, and to develop new concepts for possible future uses, including for sports events. Citizen tours were organised to discuss future uses. In the following year, in June 2017, the city

council again discussed Multihalle's future and voted to postpone the final decision until the end of 2019. This allowed more time to organise an international fundraising campaign, with the hope that the City of Mannheim would contribute a share. The goal now was to renovate the pavilion by 2023 (Eberhardt, 2019).

At the 16th International Architecture Exhibition of the Venice Biennale (2018), the city of Mannheim presented Multihalle along with archive material and new usage concepts, for the first time to an international audience.

In October 2018, the local council voted with a large majority to participate in the financing of an overall renovation. It was understood that the renovation would be complex, required some particular expertise, and could only be carried out by very few specialised companies. It was agreed that, if the federal government would guarantee a significant share of funding, the city would invest up to a third of the renovation costs.

Finally, in July 2019, the Mannheim city council decided overwhelmingly to approve the renovation of Multihalle. The administration was commissioned to carry out the structural renovation necessary to maintain the building, as well as the partial dismantling of the concrete installations, as the first construction phase. In order to commence the renovation, the city of Mannheim was now willing to invest 9.2 million euros; the federal government with funds from the federal programme "National Urban Development Projects" would finance the remaining 5 million euros. The government's reasoning was that "The project is intended to contribute to the preservation and appreciation of an architectural icon whose impressive supporting structure is an outstanding example of German engineering."

There was great relief that the structure would be rescued. In October 2020, the city council expanded its commitment to cover renovation costs; in addition, the Wüstenrot Foundation was persuaded to contribute 2.0 million euros to the project. Structural engineering design firm Fast + Epp (based in Darmstadt, Germany) won the tender to undertake a design review and restore the timber grid shell to its original splendour.

It was agreed that an optimal usage model should be found with the help of an international design competition, "in order to design a 'multi-purpose space of possibilities'" (from the competition brief). In March 2019, the jury selected three proposals for first place, out of over 50 submitted designs from all over the world. These ideas were brought together by September 2019 into a uniform design according to the jury's instructions, under the leadership of COFO Architects from Rotterdam. It was agreed that in the long term, the wooden lattice shell roof would be retained; however, the interior could change depending on the most convincing use concept. In November 2020, a majority of the local council voted for the amended redevelopment concept, which forms the basis of the current renovation efforts.

3.3 The current renovation activities: saving and reimagining a 1970s icon

Since 2011, Multihalle has been closed to the public due to water ingress and structural damage. In order to make the hall accessible again to the public as soon as possible, the renovation was divided into two construction phases. The first phase would include the renovation of the 'Small Hall' with the restaurant and workshops; while the second would involve the renovation of the 'Great Hall' and its development into an event hall, including the necessary services and renovation of the underground pipe system.

The building permit demanded that the engineering firm commissioned with the structural renovations had to submit a concept that ensured structural stability for the next 50 years. The conservation demands were also extremely rigorous. The current renovation ideas aim to preserve both the appearance and the construction principle of the supporting structure as well as possible, while at the same time enabling the necessary repairs and strengthening measures so that the hall can be used. The following section describes the recent progress made, and relies on the regular reports and descriptions in German (2023) provided by engineers Fast + Epp.

The Wüstenrot Foundation's first financial contribution to the renovation of Multihalle was to fund the trial repair of a part of the roof structure. This preliminary step was necessary to gain more knowledge and certainty concerning the future planning steps, costs, and realistic deadlines, before any measures were put out for tender. For the trial repair, the main renovation and repair concepts were tested at a 1:1 scale.

In a first step, a laser system was installed that used 40 sensors to measure every minute the movements and deformations of the roof structure. The first work package of the trial repair aimed to discover how concrete damages and dents in the roof structure could be restored to their original geometry. This was successfully completed by repairing the largest deformation of 71 cm, which was found in an area of 150 m2 above the great hall. In this complex process to recreate the original geometry of the roof structure, the reshaping was mapped and monitored with millimetre precision using the built-in laser system. The results and learning from this experiment were then incorporated into the next steps and further planning.

In a second step, from May 2021 to February 2024, the reinforcement of the wooden structure and membrane, using reinforcement slats, was tested with a series of test areas. In parallel, a large edge beam in the entrance area was successfully replaced. These glulam beams rest on two supports and hold the edge of the wooden lattice construction.

The question was how the lattice construction could best be supported and secured against wind loads, when a girder was removed. The edge beam itself consists of two solid glulam beams with additional wooden connections. After the dismantling, damage mapping was used to determine the overall condition of the structure and the causes for some of the severe damage. For example, the massive glulam edge beams that rest on steel supports were bent and twisted. The condition of the brackets for the steel supports could only be checked by removing the girder. The repair concept for the edge beams was then developed based on the findings, and this became part of the tender for these particular works (Baus, 2015; Kayser and Kovacevic, 2020; Mertens, 2020; Fast + Epp, 2023).

3.4 The 2019 ideas competition: A reuse program and concept for the future of Multihalle

A city cannot be short-sighted in such a renovation project

and needs to consider a series of factors. For example, public buildings have a special obligation to enhance the public realm, not just, because taxpayer Euros funds them, but also because they are, at least theoretically, free of the economic pressures that lead some developers to strip designs to the bare minimum. Generally, there is a limit to the amount of taxpayer money, which may be spent for renovation of a public building. The costs of a required renovation should not be to the extent that it is "disproportionate" to the total cost; it must present reasonable value for money, and ideally create a distinctive sense of place for the neighbourhood that can also build a bond of community.

A thorough analysis of space needs was conducted, a review of programmatic needs to identify the appropriate amount and type of space required, and a matrix of decision factors was developed to define the possible optimal solutions based on these factors.

When considering the suitability of Multihalle's space for future use, questions that were asked in an ideas competition included:

• What could be the vision for Multihalle's future usage, and is the current internal layout of the space appropriate for a future program?

• What modifications and reconfigurations would be necessary to adapt the structure to a viable program?

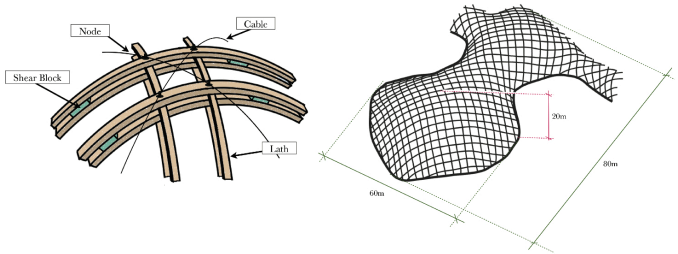
• What costs will be incurred to prepare the spaces for the new use?

New contemporary ideas for usage of the disused building needed to be developed, and a call for concepts was published; this aimed to generate sustainable and viable options to redevelop and convert the structure into a leisure, sports and cultural complex. The complex should also be used again as a highly innovative exhibition and events facility. Monument preservation advocates that interventions be kept as minimally invasive as possible. However, the aim was not to create a monument, but rather a 'living place'.

An international ideas competition was organised in two stages in 2019/20, in order to answer above questions, and the competition brief (programme) stipulated:

> *The Multihalle's roof construction should not only provide the necessary setting for its visionary use, but also symbolise the idea of a 'Democratic Umbrella' in public perception using the iconic architecture. The objective of this competition is therefore to design new utilisation options for Multihalle and to express these through its architecture.*

In March 2020, the jury selected the design proposal submitted by COFO and PEÑA Architects, a Spanish team based in Rotterdam. The jury thought that their design proposal represented a concept "with the greatest development potential at the highest architectural quality" (Baunetz, 2020). The spatial organisation is aligned with four "main catalysts of urban life": tent/square, platform/stand, plate/atrium, and roof/stage. The architects proposed only minimal interventions that would not touch the roof structure. Their concept includes participatory engagement with the residents of the local neighbourhood, and will soon commence once the structural renovation is more advanced (See Figures 5).



The concept imagines various new small structures along a so-called 'Hallenallee' – a pedestrian axis that will be extended at both ends into the park – thus offering residents and visitors a better connection to the city's public transport. The architects were commissioned to further develop the usage concept (see Figures 5). Near the middle of the Hallenallee, in front of the entrance to the large hall, the architects placed a rectangular cube, in stark contrast to the soft shape of the roof. The cube provides a stage for artistic performances and events. "While many recognise the Multihalle as a technological achievement, fewer are aware of its profound social ambitions, and the social dimension of the project deserves more attention," said Guillem Colomer of COFO Architects (in conversation with the author, 2024).

Thanks to his holistic approach, Frei Otto was always a step ahead of his time. Based on Otto's original desire to connect people and nature, the renovation and reuse concept will further dissolve the separation between inside and outside. The new membrane will restore the transparency of the original design. Elements that currently interrupt the wooden lattice shell, such as outdated plumbing pipes, will be removed, and Multihalle will be sustainably revitalised to recreate a unique, open and dynamic space. Internal interventions will be strategically placed on a diagonal axis between the large hall and the small hall with the catering area, to preserve and strengthen its openness. Both halls will be re-programmed to create a versatile structural framework for future developments.

The grandstand will be recreated in the main hall by equipping the existing concrete platforms with wooden benches; these will serve as sound absorbers and integrate the technical elements. The railings are to be removed, to create a continuous uninterrupted space. The small hall will be converted into a second multi-purpose hall by turning the technical rooms on the upper floor into workshops. A new restaurant is being built on the

ground floor. A glass facade creates flowing transitions between inside and outside, and reinforces the extraordinary feeling of space underneath the self-supporting shell.

When it opened at BUGA 1975, Multihalle offered a unique, colourful experience. During the renovation, great care is being taken to restore the original features – including the original colours and elements such as chairs and curtains. All new interventions will be carried out using a clear, distinctive design language, and in contemporary materials, to clearly differentiate between new and old.

In accordance with the usage concept, the semi-circular grandstand can be arranged in different ways, using the wooden seating modules. Below the concrete steps, offices, smaller event rooms and studios will be built. The sanitary facilities and technical infrastructure will also be renovated.

The architects of Mutlihalle's interior are also assisting with the architectural qualities of the shell and landscaping; they started a process of participation and dialogue involving the citizens of the local neighbourhood. One of the architects, Guillem Colomer, said, "It is important to recognise the unique opportunity that the new Multihalle represents – for the neighbourhood, for Mannheim, and for the entire region" (in conversation with the author, 2024).

In July 2021, the initial funding for the renovation was finally agreed upon: 4.7 million euros were committed from the federal government, and the City of Mannheim approved 9.2 million euros (Eberhardt, 2019; Möller, 2019). However, in 2022, with the findings from the trial phase available, it became increasingly obvious that the initial funding would not be sufficient, and that the renovation would take more time.

In particular, the roof repair phase would be longer and require additional funding. The detailed examination of the roof damage commissioned by the city of Mannheim in 2020 revealed a much greater need for repairs than was originally expected. For time and cost reasons, the usage plan and interior works were further postponed until after the required repairs have been completed (this is expected by 2025). The additional costs amounted to 6 million euros, which resulted in a total of over 20 million euros. The individuality and diversity of the damage to the various structural components meant that implementation decisions on the most suitable renovation pathway could only be made during the trial phase, and would be subject to corresponding cost uncertainty. New cost estimates published in December 2022 indicate a likely total renovation budget of possibly 36 million euros. However, calls to abandon the planned works did not receive majority approval.

3.5 The initial trial repair phase delivered the knowledge of the optimal process

The main concern of the renovation of the Multihalle is to preserve the original supporting structure of the roof, which is characterised by the delicate wooden lattice shell and the translucency of the roof skin. However, the revitalisation of Multihalle could only be implemented through several individual phases, testing measures and a wide variety of partners and funding providers. In their recent structural progress report, engineers Fast + Epp reported (2024) that the initial testing and trial repair phase has been successfully completed in February 2024.

With the comprehensive and unique renovation project underway, the team reached an important milestone with the successful completion of the trial repair phase, marking significant progress towards the main renovation. The completion of the pilot repair phase with three representative test areas provided a profound understanding of the load-bearing behaviour of the structure and made an important contribution to preserving the authenticity of the project.

In many ways, it is pioneering work in monument renovation and preservation. The renovation of the Multihalle is not only a technical challenge, but also a commitment to the preservation of the cultural heritage from the 1970s. The city of Mannheim, together with its consultants and scientific advisory board, decided on a path that went far beyond the normal steps of renovating a building. Reinforcement and repair approaches were first tested during the trial phase — a unique methodical approach to develop the optimal concept. "With the knowledge gained from the test areas, the scope of renovation could be realistically determined and an optimal construction process decided", said Mannheim's mayor of construction, Ralf Eisenhauer. "Fifty years ago, the construction of the Multihalle was a ground-breaking experiment for grid shell construction worldwide. The same applies to its renovation. However, public procurement law does not leave much room for exploratory approaches. The Wüstenrot Foundation made this possible by financing and organizing the test areas. We are proud of this contribution, in which mistakes were explicitly allowed and created the greatest possible security for the tendering and renovation of the hall roof," added Philip Kurz, Managing Director of the Wüstenrot Foundation (press release, 2024).

There are no recognised technical rules or standards for such type of renovation, making it difficult to procure and adding to the risk of the endeavour. The findings from the trial phase provided a profound understanding of the load-bearing behaviour of the structure and makes a decisive contribution to preserving the authenticity of Multihalle. In the course of the renovation, an adaptation to today's building regulations must be made, particularly with regard to fire protection and stability, while the historical character of the original should be preserved in its original form.

As mentioned, there were three test areas: One of the test areas

focused on the installation of reinforcing slats and examined transition details, the installation of shear connectors, the connection details to the edge beam areas and the replacement of the bolts and stiffening cables. Another test area examined the recovery of a dent in the roof structure to determine whether the grid could be pushed back again without causing damage. For this purpose, a laser system was installed that uses 40 sensors to measure movements and deformations of the roof structure every minute. A glulam edge beam was replaced as part of the third test area (See Figures 8).

Figures 8: Images of the initial trial repair phase (completed in 2024), which included three test areas to gain a better understanding of the optimal renovation process. The exchanged and reinforced slats are clearly visible; the replacement of the roof covering membrane. Images by Fast + Epp (2024).

3.6 Overview of the next steps of planned structural renovation upgrades

The test areas repaired during the trial repair phase delivered the detailed knowledge required to formulate a comprehensive repair concept, provided more certainty on costs and eliminated potential implementation hurdles. The goal was to repair the preserved building structure in the spirit of Frei Otto, gently and with minimal invasiveness; i.e., to remove or replace as little existing material as possible.

The survey found that in the large hall, reinforcement of the original wooden structure was only partially necessary. Crossed straps with reinforced slats on the bottom increased the structural stiffness. The original geometry was restored in the dome area, so that the reinforcement measures could be kept to a minimum. The small hall received additional battens in the edge areas towards Herzogenriedbad. In the tunnel areas and in the area towards the great hall, which is called ‘banana’ (because of its shape), reinforcements were installed for the nail strips and in the lower ‘hip areas’, in the form of additional battens.

There will also be an entirely new, translucent PVC membrane to replace the previous, damaged one. It is white, with approximately 10 per cent light transmission. Additionally, five transparent windows were restored using a clear high-performance ETFE-film.

The first roof repairs began in spring 2021 and the trial phase was completed in February 2024. With the knowledge gained during the careful trial renovation process, the detailed structural survey, and the design competition for new usage concepts, a new chapter has begun for Multihalle – one that will bring it into the future, while maintaining its significance and original ambitions.

4 Other grid shell projects since Multihalle

Today, the interest in Multihalle is immense, and extends beyond the architectural community. The building’s impact cannot be overstated. Since its completion in 1975, Multihalle inspired numerous other architectural projects to use wooden grid shells, including:

- A temporary building for the “Silk Road Exposition” in Nara, Japan (1988) used a similar technology to the Multihalle Pavilion; it was designed by Itsuko Hasegawa Atelier (demolished).
- Stuttgart-based structural engineers Schlaich Bergermann & Partners realised two wooden grid shell roofs: one is a grid shell over a swimming pool in Neckarsulm (in 1989); and the other is for the History of Hamburg Museum (in 1993).
- Shigeru Ban’s Japan Pavilion at the Hannover EXPO, 2000; in collaboration with Frei Otto, a grid shell of circular paper (cardboard) tubes.
- Flimwell Woodland Enterprise Centre, a modular grid shell designed by Feilden Clegg Architects and Atelier One in the UK, 2000.
- Savill Garden grid shell, 90 by 25 m in plan, located in Windsor, by Buro Happold and Glenn Howells Architects, UK, 2006.
- Weald & Downland Open Air Museum by Buro Happold and Edward Cullinan Architects: a smaller, 48 m long two-layer wooden grid shell built in Singleton, UK, 2022.
- The public library Media Cosmos in Gifu, Japan, designed by Toyo Ito Architects, 2015: screwed together on site as a multi-domed wooden lattice grid shell.

All the aforementioned wooden grid shells have a shorter span and are smaller than Multihalle. According to Liddell, “it is unlikely that such a large and complex structure as in Mannheim would be built again” (2015, 49). For example, Superior Dome is a domed stadium on a university campus in Michigan, United States, completed in 1991; it has a regular wooden double-curved dome

and is not a real grid shell.

In the 1970s, several architecture schools conducted design and construction experiments for small timber grid shells. For example, Florian Beigel designed and constructed a grid shell in 1975 with his students at North London Polytechnic, based on the principles he learnt earlier from working with Frei Otto (before coming to London in 1968, Beigel had worked as the intermediary between Otto and Guenther Behnisch's office during the early design development of the Munich Olympic Stadium roofs).

Alternatively, smaller grid shells could also be built in bamboo, which has the flexibility and strength necessary for the spherical shape. More recently, Achim Menges and Jan Knippers at the Institute for Computational Design and Construction (ICD), University of Stuttgart, have further developed the concept of the lightweight wooden grid shell into a computer-based "biomimetic shell", which focusses on robotic prefabrication, automated assembly, whole- lifecycle analysis and the reduction of material consumption. The curving geometry is made of a plate skeleton of hollow cassettes made of three-layers of spruce boards, and this segmented shell construction is completely deconstructible and reusable (Nair, 2023). Biomimetics or biomimicry means the emulation of natural systems and elements of nature for solving complex human problems.

Steel grid shells are more frequently used and have been built over the last 30 years; they have benefitted from the experience gained from their wooden predecessors, and new developments in computerized steel fabrication. Some of the most prominent steel grid shells include the following:

- The Eden Project built in 2000 in Cornwall, UK, above a disused clay pit; designed by Nicholas Grimshaw.
- The glazed roof grid shell covering the Great Court at the British Museum, London, which was designed by Foster + Partners and opened in 2000.
- The steel grid shell at the Formula 1 racing track at Yas Island in Abu Dhabi (UAE), designed by Asymptote Architecture in 2009.
- The steel diagrid shell at the King's Cross Station concourse in London, designed in 2012 by John McAslan + Partners.
- The Amazon Spheres in Seattle, Washington (USA), consisting of three spherical glass domes in steel, designed by NBBJ in 2012.
- More recently, numerous other steel grid shell structures have been built around the world, including in the Netherlands, Germany, France, China and Singapore.

5 Conclusion: celebrating lightness – the influence and relevance of the Multihalle Pavilion

The Multihalle in Mannheim is a remarkable example of lightweight architecture celebrated for its advanced structural design and distinctive shape. Although the Multihalle Pavilion was originally meant to be a temporary structure, it is still standing today, and its renovation and redevelopment is well under way. The Mannheim grid shell is an innovative, pioneering building, which set extraordinary technical and social ambitions. Apart from small grid shells realised by Frei Otto in the 1960s, it had no predecessor, and was based on the results of experimental design research work carried out at the Institute for Lightweight Structures (IL) at the University of Stuttgart. Overall, in the 1970s it was a risky endeavour – one that Otto and Mutschler were brave enough to undertake and manage.

Innovation in structural engineering is widely relevant, because it helps the industry and profession to move forward and better cope with emerging technological, environmental and social change. Innovation is about new tools as well as new processes that are implemented (a good example of this is today's adoption of building information modelling (BIM) standards by the architecture, construction and engineering professions).

In 1975, the pavilion was a significant achievement due to its unusual shape and large span, as well as for its innovative use of timber to create a complex and flexible lattice, which was previously unrivalled in timber engineering. Today, increasing numbers of architects and urban designers throughout the world are becoming aware of Mannheim's most important modern architectural monument.

The unique building with its elegant form has attracted many favourable comments. Worldwide, experts agree that Multihalle is an important icon of architectural engineering, and an expression of a time that was characterised by a search for new and freer forms of building and society. Mario Carpo mentions Multihalle in his seminal book (2012); he calls it a pioneering key building of the 20th century, which foresaw the "digital turn in architecture" that was to occur 20 years later with the rise of nonlinearity and curvilinearity – thanks to advances in computer-based and parametric design.

In 2015, the engineer Liddell noted "the building has currently little use and the renovation work will be very costly". In general, due to their high complexity and cost, grid shell structures have rarely been built. The IL Institute was interested in establishing industrial standardisation and regulations for future grid shell structures, in order to make them more cost-effective. Such standards are central to any modern mass-production methods and economies of scale; it is simply more affordable to make identical copies of fewer different components, and combinable structural members that can be replicated and used by a larger market (Carpo, 2012). Nevertheless, so far, grid shells have been one-off structural solutions and have not entered the mainstream.

In recent years, Multihalle has been closed and inaccessible; however, it still attracts great interest and is on the way to its awakening, eagerly awaited by the global architectural community. Overall, Multihalle is an engineering and architectural masterpiece, but its authentic renovation presents serious challenges (as described previously). The planned reinvention and rebirth of Multihalle is also symbolic of a transformation and renewal process of post-industrial cities such as Mannheim.

Multihalle still embodies the optimism of its time. It is also considered a major work of organic architecture, and to this day, it inspires architects, urban planners and scientists around the world. In recent years, Multihalle has become the profoundly inventive symbol of Mannheim's urban renewal process. The great commitment it generates makes it possible to develop and revitalise it as an open place of social interaction, cultural engagement and participation, at the local and international

scale.

In conclusion, the renovation of the Multihalle is a technical challenge as well as a commitment to the preservation of cultural heritage from the 1970s. With the progress made in the renovation process and a refined usage concept in place, a new chapter has begun for Multihalle – one that will bring it into the future while preserving its significance and original ambitions. The renovation will maintain its original design ideas and awaken an open space for an 'open society', true to its experimental origins, its unique flow of spatial qualities, and its intimate integration within the urban topography of the parklands. Based on the ideas of the radical unbuilt project 'Fun Palace' (1963-1973), Multihalle exists today (and will be relaunched again soon) as an experiment to expand the possibilities of how people can interact with architecture, without architecture arbitrarily limiting that interaction.

Now, the aim is to complete the renovation works by 2027; after this, the works for the reuse concept by COFO Architects can commence, so that a full completion and final re-opening of the regenerated Multihalle is expected for end of 2028. By then, Multihalle was closed to the public for 17 years. The renovated structure, once it has reopened, will endure as a reminder of Frei Otto and his ingenious team, and their inventive ways of thinking about structures.

In the last eight years, the renovation costs have significantly grown (in fact, these have doubled since the initial 2016 cost estimate), and the completion of all the planned works will require an immense commitment and dedication by all involved. Despite all the struggles, today, the future of Multihalle looks positive, as the City of Mannheim is working with a dedicated group of engineers, architects, builders, local residents and universities on a sustainable concept for the pavilion's future. This will ensure the structure's long-term preservation, which is on the way to becoming again an active part of the city.

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Exhibitions and documentaries on the work of Frei Otto and the Multihalle Pavilion (Selection):

In 1971, Frei Otto was recognised with his first monographic exhibition at the Museum of Modern Art (MoMA) in New York. A redesign of this exhibition later travelled from 1975 to 1977 to venues in North America, Europe, Asia and Australia.

In 1982, the exhibition "Natural Constructions" was organised by the Institute for International Relations in Stuttgart and shown in Goethe Institutes in approximately 80 countries.

2005 TV Documentary: Frei Otto. Von Seifenblasen und Zelten. Germany, 2005, 60 min., by Louis Saul, Production: SWR, arte (22 April 2005); from 38:10 min: Frei Otto with Joachim Langner, Ian Liddell and others, assessment of the state of the Multihalle Pavilion.

Since 2013 in the model collection of the Deutsches Architekturmuseum (DAM), Frankfurt a.M.:

Multihalle Mannheim – Haengemodell zur Bestimmung der Gitterschale des Hallendaches (by C. Weber), in: DAM – Modellsammlung, 2013. See also: Elser, O. and Schmal, PC. (2012). Das Architekturmodell – Werkzeug, Fetisch, kleine Utopie, Ausstellungskatalog DAM, Zürich/ Frankfurt a.M; available online: http://archiv.dam-online.de/handle/11153/187-011-001

2015 Video (4 minutes), Tributes and the Jury Laudation produced for the prize ceremony for Frei Otto award of the Pritzker Architecture Prize on March 2015, available online: https://www.pritzkerprize.com/laureates/frei-otto

2016 Exhibition at the ZKM Zentrum fuer Kunst und Medien, Karlsruhe (2016). Frei Otto. Denken in Modellen – Projekte. Der Olympiapark in München, die Multihalle in Mannheim, und Stuttgart 21. A short video available online: https://zkm.de/de/media/video/frei-otto-denken-in-modellen-projekte

2017 Exhibition curated by Robert Häusser und Marco Vedana: Raumwunder: "Multihalle"

Architekturfotografie im Haus der Architekten in Stuttgart, Germany, from June to July 2017.

2018 Exhibition at the 16th International Architecture Biennale of Venice, Italy (2018). Sleeping Beauty – Reinventing Frei Otto's Multihalle, organised by saai and the City of Mannheim, from May to November 2018.

2019 Exhibition Multihalle – Democratic Umbrella, at Wechselraum des BDA in the Zeppelin-Carré, Stuttgart, from April to June 2019.

Related websites:

City: Website of the City of Mannheim on the renovation of the Multihalle shell structure, and online blog on the current progress of the works:

https://mannheim-multihalle.de/ and https://mannheim-multihalle.de/blog/

Architects: Website of COFO and PEÑA Architects (Rotterdam) who are currently working on Multihalle's redevelopment

concept:
https://cofoarchitects.com/work/multihalle-renovation
The architects also started a process of participation and dialogue involving the citizens of the local neighbourhood in the transformation process, see here:
https://cofoarchitects.com/work/multihalle-activation
Baunetz (2020) has also reported on the architects' winning usage concept, and the article with images (13 March 2020) is available online: https://www.baunetz.de/meldungen/Meldungen-COFO_und_PE-A_mit_Nutzungs-_und_Umbaukonzept_beauftragt_7172421.html
Engineers: Website of Fast + Epp global engineering design firm who are currently involved with the restoration works of the grid shell: https://www.fastepp.com/portfolio/multihalle-gridshell/

Further information on Multihalle's grid shell structure (in German):

https://www.proholz.at/zuschnitt/19/auf-den-kopf-gestellt?fbclid=IwAR2tT4fbhU8XOJ-l-kLsSDnK5YDLTQdEpnaGV8Bz8viJMPeuU4HYmPrgCRw
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Fact sheet: General information on the Multihalle Mannheim and its structure

Multihalle Pavilion Mannheim: constructed: 1973–1975.

Timeline: The Multihalle Pavilion was built in only 16 months. Construction began in December 1973, and the main lattice was gradually erected from April to June 1974. The Multihalle structure was in place by November 1974, and the interior works were completed by March 1975. The garden exhibition opened to the public in time on 18 April 1975.

Client and owner of the structure: The City of Mannheim

Address: The building is located in Herzogenriedpark in Mannheim, Max-Joseph-Strasse 64.

Architects and engineers: Carlfried Mutschler, Joachim Langner (architecture), and Frei Otto (structural design and architectural engineering). It was a joint effort with numerous other engineers involved as team members under the leadership of Frei Otto (lead engineer); this included the engineering consultancy Ove Arup and Partners in London (today: Arup), and involved two young project engineers, Ted Happold and Ian Liddell. Happold (1930–1996) and Liddell (born 1938) had both worked earlier on the roof of the Sydney Opera House (and both later founded the engineering consultancy Buro Happold).

The Multihalle Pavilion was one of the first buildings in Germany whose layout drawings and components were designed and drawn using a computer, when this method first entered architecture as a design tool and drawing machine. The University of Stuttgart used photogrammetry to capture the shape of the hanging models. The captured shape was then converted into a digital model, so that the design of the timber lath grid could be calculated and verified (Frankhaenel and Lepik, 2020). The datasets were created on a CDC 6600 mainframe computer (generally considered to be the first successful supercomputer) at the University of Stuttgart. These datasets were subsequently used for the pioneering construction planning – a new technique at the time, which helped to design and fabricate the complicated shapes and angles of the laths (long before computer-based finite element analysis was introduced). Today it would be much easier to calculate such a non-linear structure using evolutionary algorithms in simplifying non-standard, lightweight catenary wood structures, with advanced computational methods to reduce construction complexity while emphasising the use of timber as a sustainable, low-carbon construction material.

Frei Otto's rope net suspension models and hanging chain models were used in London as the basis for the structural analysis and calculations of the geometry. Drawings and specifications were prepared from the measured model. The computer-generated mathematical model yielded very similar results to the analogue one, and to what the engineers had found in the hanging chain model. Ove Arup and Partners – and Structures 3, the engineers hired for the project – provided the proof of stability with final structural calculations using conventional, analogue methods; in addition, other consultants also provided input on the final calculations and construction details of the experimental grid shell. The findings indicated that the edges, in particular, needed

to be strengthened. Klaus Linkwitz conducted the computer force density analysis.

The dimensions of the Multihalle Pavilion: A supporting structure of wooden slats (laths), laid crosswise in two or four slats on top of each other. The engineers decided to double the laths, creating four (rather than two) layers of wooden laths with a cross-section of 50 by 50 mm. The distance from each other is 50/50 cm. Wood from western hemlock and pine trees was chosen for the laths because it was available in the long lengths needed.

- Drill holes at the crossing points: 144,000, with 34,000 bolts
- Edge circumference: 685 m (rope-supported edge: 35 m, arches 135 m)
- Rope net: 7,150 m length
- Hall size: 10,500 m2 (113,000 sq ft)
- Event capacity: 2,500 people
- Total length: 160 m (525 ft)
- Total width: 115 m (377 ft)
- Dome height: 20 m (66 ft)
- Largest transverse span: 60 m (197 ft)

Roof covering: Roof area: 9,500 m2 (102,000 sq ft).

The roof covering is a critical element and problem in itself, for such a large dome with a wide variety of curvatures. A thin, watertight, translucent PVC membrane covers the entire shell, with 30 per cent light permeability. The original roofing was in Trevira fabric; it was blackened with a bronze tint, PVC-coated, broadloom, overlapped and heat-sealed at the joints, and mounted on nail battens with Bukama clips. Thanks to the matt translucent membrane, the interior is evenly illuminated with daylight. The first canvas soon developed leaks, and was replaced in 1981 by a white, more conventional and durable tarpaulin.

Construction process: The installation process is critical for grid shell structures. In erecting the roof of Multihalle, the grid shell was first laid out flat on the ground with loosely connected nodes, and then pushed up into shape with the help of scaffolding towers. The wooden lattice was gradually lifted into the shape of the model. The bolts were then locked into place and the boundaries of the shell fixed so that the roof could bear its own weight. After being attached to the edges, adjusted and fixed, the structure was finally covered with the translucent tarpaulin, a PVC-coated polyester lattice fabric. Finally, an asymmetric load test with water barrels was carried out to ensure the building's structural stability.

Recognition: In 1978, Multihalle was awarded the Hugo Haering Prize, the most important architectural prize in the state of Baden-Wuerttemberg. In 1998, the building was listed as a cultural monument, for scientific and local history reasons, making it one of the youngest monuments in Germany. The pavilion has been closed to the public since 2011 due to structural damage from water ingress. Despite its monument status, the building deteriorated, and in 2017 came close to demolition. It is now considered a cultural monument of particular importance.