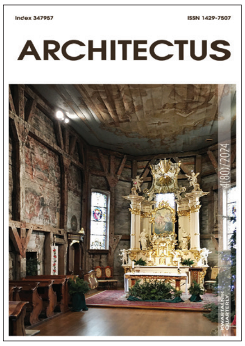

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Retro-digitising non-Euclidean physical models in construction history: Challenges, results and potentials

Abstract

A range of established methods are currently available for the production of digital models to document, survey, or further develop buildings. Equipment and other technologies have been adopted from other disciplines, such as geodesy, and further developed specifically for the construction industry. These methods, therefore, have a very specific purpose and quickly reach their limits when they leave this primary area of application. As part of a research project "Last Witnesses – Physical Models in Civil Engineering" funded by the German Research Foundation (DFG SPP 2255), an attempt was made to transfer known methods of retro-digitisation from architecture to smaller-scale objects to create digital representations. These small-scaled objects are so-called physical models (Messmodelle), a particular type of model mainly used in civil engineering in the past to test load-bearing structures. The models were mainly used in the 20th century to calculate the behaviour of complex structures; however, both the model building and the mathematical calculations were very time consuming and prone to errors. From the 1960s and 1970s onwards they were replaced by the first powerful computers in the construction industry.

This contribution will discuss the special characteristics of these physical models and why they were replaced by computers. We describe the applicability of the different non-destructive methods of retrodigitisation and analyse the advantages and disadvantages of the structured light 3D scan, the 3D laser scan, and photogrammetry. In a further step, the potential of the produced digital twins in different contexts, such as restoration, engineering, or architectural history, will be demonstrated.

Key words: architecture, physical models, reverse engineering, digital twin, data storage

Research Project "Last Witnesses – Physical Models in Civil Engineering"

Physical testing models form a special class of models that were mainly used in the field of civil engineering, until the advent of powerful computers in the construction industry from the 1960s onwards. Such models served to analyse, understand, and finally, even dimension and test load-bearing structures (Bühler, Weber 2022). While form-finding models were used to establish the geometry, measurement models were used to calculate forces, but also allow for experimentation with different forms and materials. Such physical models – in German called *Messmodelle* – were mainly in use during the 20th century, when drawing, dimensioning, and calculating the shape and construction of cable bridges, dams and wide-span lightweight structures or shells was time consuming, or not even possible with the known calculation methods[1].

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[1] The research project "Last Witnesses – Physical Models in Civil Engineering" was part of the priority program "Cultural Heritage Construction" (SPP 2255) funded by the German Research Foundation DFG from 2020 to 2024. Scientists from the fields of construction history, engineering and restoration sciences have been cooperating in the project (DFG 2024).

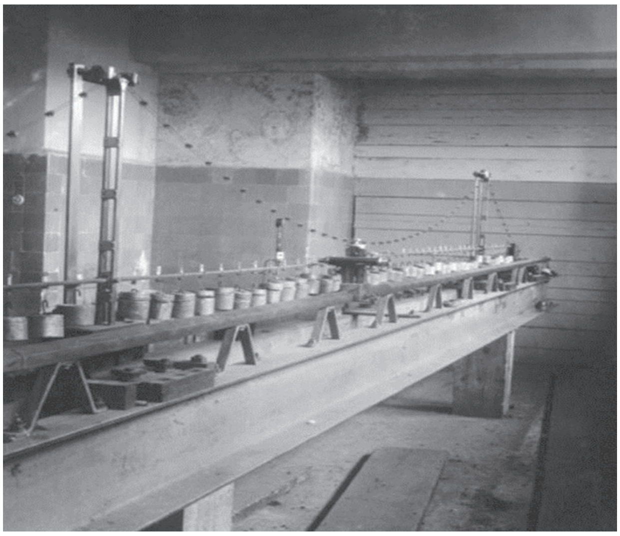

Fig. 1. Physical model (scale 1:100) for the bridge over the Rhine at Rodenkirchen proposed by Fritz Leonhardt (photo: saai Karlsruhe, collection Fritz Leonhardt)

Il. 1. Model fizyczny (skala 1:100) mostu nad Renem w Rodenkirchen zaproponowany przez Fritza Leonhardta (źródło: saai Karlsruhe, kolekcja Fritza Leonhardta)

One early example is the scale model for a suspension bridge over the Rhine at Rodenkirchen near Cologne, built in the 1940s by the Stuttgart Material Testing Institute (Materialprüfungsanstalt Stuttgart – MPA). As it was very difficult to calculate the deformation of this statically overdetermined structure, the Stuttgart civil engineer Fritz Leonhardt (1909–1999), who led the project, had commissioned this physical model on a scale of 1:100, which is documented in photographs, today preserved in the Stuttgart University archives (Fig. 1).

Like architectural models, physical models at the same time could serve as a communication medium and planning tool, but unlike these, they often were damaged or even destroyed in the measuring process. For example, models of concrete shells have been tested for cracking until failure, resulting in the destruction of the model. Thus, the model itself was not preserved, but data from the impact under load was documented as shown in photographs – or even more abstract data deduced from these. The findings of the research project are therefore only a very small number of surviving objects, mostly only fragments of experiments. The experimental set-up, including the measuring equipment, has not survived at all, as it was reused for further experiments. The appendix lists all the models researched (based on Addis 2021), including those objects that can only be reconstructed using images or archival material (appendix). The *Table of Surviving and Lost Models* allows for a preliminary evaluation of the ratio between photographic and material remains of testing models and it can be stated that only a few physical models, or more precisely fragments of these, have survived or found their way into collections or archives. This may generally have occurred due to the engineers' lack of historical awareness and their general underestimation of the importance of construction as cultural heritage (Schmid 2023).

Fortunately, certain physical models like the model for the Olympic roof construction for Munich in 1972, designed by the famous architect Frei Otto (1925–2015), have ever been an object of broad public interest. The filigree wireframe model is still on public display in the visitor centre of the Olympic Park in Munich today and offers detailed insights into a very courageous phase of civil engineering (Fig. 2b). It fascinates as an in-between object: At the same time, it is very specific concerning forces but also abstract concerning form.

From analogue to automated – limits of physical models

The very few still existing models are precious objects and knowledge sources of engineering practice between 1920s and 1970s. All the more so, as they took place at the thresholds from analogue experimentation to early data processing with computers, developing novel interfaces. For the Munich Olympic Roofs, Frei Otto's institute for lightweight construction (Institut für Leichte Flächentragwerke – IL) at Stuttgart University built several form finding models of polyester mesh on a scale of 1:200. For the statical calculation of the execution of the cable net construction, physical models at a scale of 1:125 were developed (Fig. 2). The cable net in the model is made of stainless steel wires with a diameter of 0.2 mm and the edge cables are made of copper wires. In order to determine the deformations under load, the model was loaded with steel weights that could be moved by means of a pneumatic substructure. In addition to strain gauges and protractors, photogrammetry with a large number of cameras was also used in these tests, which is why they are also known as multimedia tests. After these tests, the models were also to be used to determine the cut pattern, used for the production and installation of the rope net. Due to the size of the structures and the maximum working range of the IL measuring table, the chosen scale was 1:125. The small scale, as well as the high preload and its tolerance values, meant that a very high level of precision in model building was required. The cutting pattern information was obtained through photogrammetry at the Institute for the Application of Geodesy in Civil Engineering (Institut für angewandte Geodäsie im Bauwesen – IAGB) at the Stuttgart University under the direction of Klaus Linkwitz (1927–2017). As it would not have been possible to build all the necessary detailed models in time, two new, computerized methods were used to determine the dimensions of the roof cutting patterns of the Olympic Park, in addition to the classic manual measurement at the IAGB. Klaus Linkwitz and his Stuttgart colleague John Hadji Argyris (1913–2004) set about calculating the geometry and, derived from this, the cuts of the cable nets, taking into account material and temperature influences under pretension. A CDC 6600 super computer from Control Data Corporation at the Stuttgart University was used for this purpose. Argyris worked on the sports hall based on the finite element method (FEM), which he co-developed. In FORTRAN IV, a program was created in which the topology (Gade et al. 2022) of a network is described, an iterative

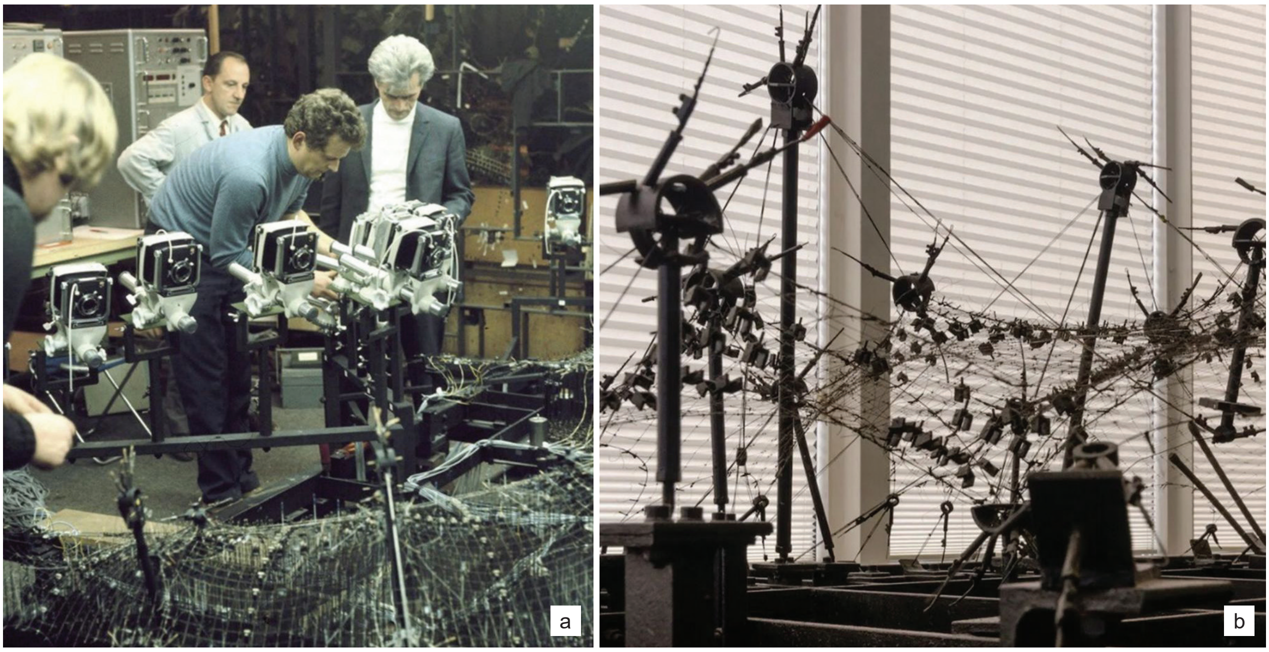

Fig. 2. Multimedia experiments on the model of the stadium roof in Munich at a scale of 1:125:
a) in 1964–1972 (source: ILEK Stuttgart), b) in 2023, at Visitor Centre of the Olympic Park in Munich (photo by B. Schmid)

Il. 2. Eksperymenty multimedialne na modelu dachu stadionu w Monachium w skali 1:125:
a) w 1964–1972 (źródło: ILEK Stuttgart), b) w 2023 r. w Centrum dla zwiedzających Parku Olimpijskiego w Monachium (fot. B. Schmid)

determination of equilibrium is carried out, various load cases can be simulated, and drawings can be created. Linkwitz and his team developed a different calculation program based on the method of least square deviations, which was used immediately after its completion in May 1970 for the calculation of the stadium, and subsequently for the cable nets of the two minor cable net constructions at the Munich Olympic site. The very effective and at the same time extremely robust and computationally efficient numerical method developed by Linkwitz under great time pressure is known today as the force density method for determining the shape of prestressed cable meshes and is also used for textile membrane structures.

The justified concerns of engineers as well as their curiosity about innovative computer-aided methods have contributed to the fact that, at the height of the development of measurement modeling statics, its end was also in sight. Two essential computer calculation tools were developed in this way, which are still used in daily calculations today (Schmid et al. 2024; Schlaich et al. 1972).

Materiality in models – appearance and behaviour

Models are always a reduction to the important aspects of an object. Everything that seems unimportant is left out. The simpler the model, the better, as the German physicist Heinrich Hertz (1857–1897) said (Ortlieb 2008). When a physical model was created for a building in the high modern era, the reduction to the essentials was an important goal. Creating the models was usually a time-consuming process. In the model for Munich's Olympic Stadium, for example, all the nodes of the cable mesh had to be manually knotted, which led to only representing every fourth mesh in the model.

The question of materiality played a major role in physical models. According to similarity mechanics, a material with similar properties was usually chosen. But there were limits to scalability, as the model of the Alster indoor swimming pool that has survived at Stuttgart University shows. This huge model realised by the Stuttgart Institute of Model Statics (Institut für Modellstatik – IMS) is made of acrylic glass, while the roof of the realized building (completed in Hamburg 1973) was made of reinforced concrete (Fig. 3a) (Schmid, Weber 2021). The problem with scaling the material was the grain size of the sand added to the concrete. Preliminary investigations at the IMS resulted in a minimum thickness of 1 cm for the planned model made of micro-concrete. The resulting scale would have made the model very large. The ratio of the internal and external surfaces changes drastically when scaling, because while the surface area only increases quadratically, the volume's growth is cubic. Furthermore, the theory of elasticity requires materials with a homogeneous continuum for the calculation of load-bearing structures, which is difficult to achieve with natural building materials. Therefore, a material with similar physical characteristics, such as a similar modulus of elasticity, was chosen to build the model.

Acrylic resin proved to be a suitable modelling material for simulating concrete elements, not only for the Hamburg shell model but also for the many models created by the Swiss engineer Heinz Hossdorf (1925–2006). In addition to its homogeneous nature, it was easier to process and prepare for the experiments. As it is transparent, cracks and air inclusions are easily recognizable and the strain gauges could be placed exactly on top of each other, which

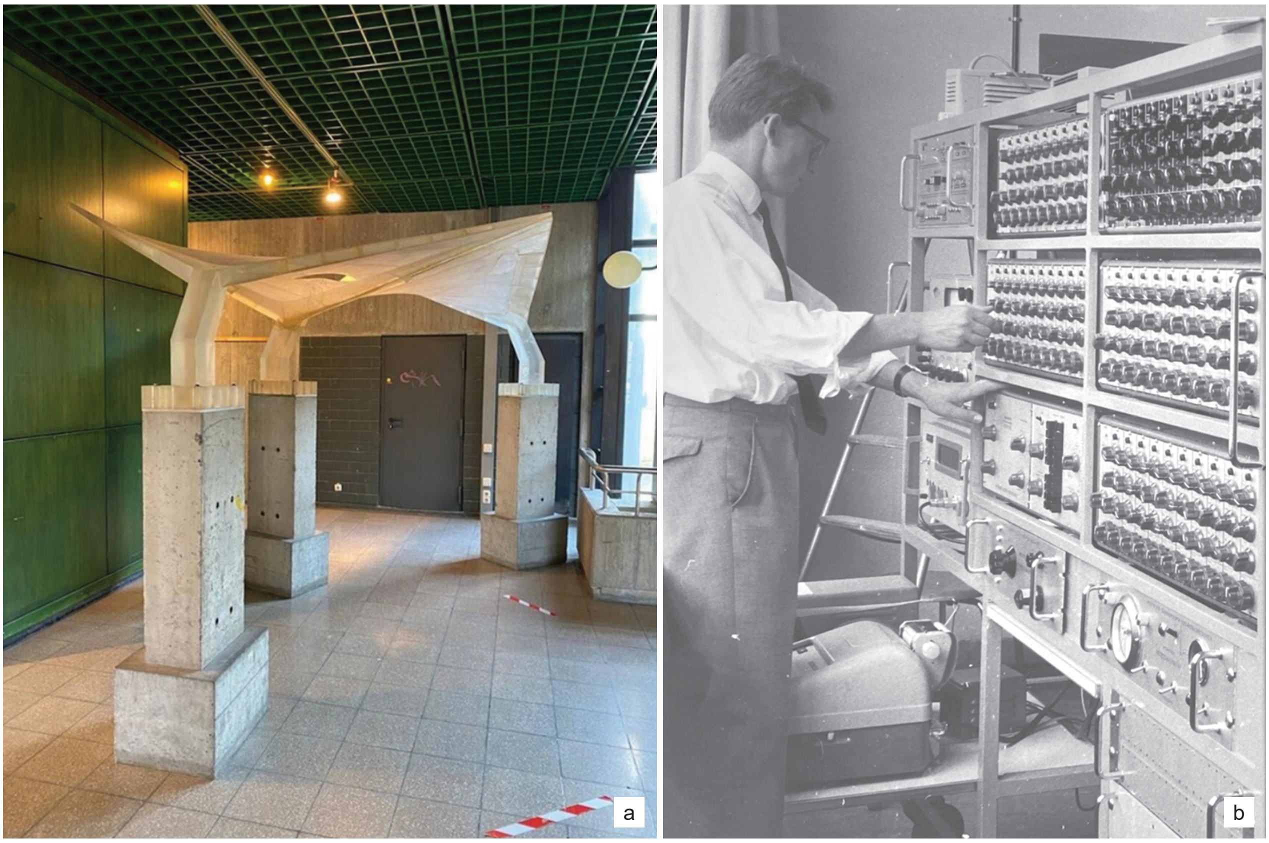

Fig. 3. A surviving model and its measuring device: a) the acrylic model of the Alster swimming pool in Hamburg (photo by B. Schmid), b) automatic measuring system and pinhole printer at the IMS (source: Stuttgart University Archive, collection IMS)

Il. 3. Zachowany model i jego urządzenie pomiarowe: a) akrylowy model basenu pływackiego Alster w Hamburgu (fot. B. Schmid), b) automatyczny system pomiarowy i drukarka otworkowa w IMS (źródło: Archiwum Uniwersytetu w Stuttgarcie, zbiory IMS)

led to more accurate measured. Strain measurements were made with strain gauges, an automatic measuring device and edited via pinhole printers (Fig. 3b) (Hossdorf 1971).

Only a few of these models and of the complex measuring equipment, which illustrate the transition from analogue structural calculations to computer-based methods in the 1970s, have survived. These few surviving models store knowledge for the engineering and technical practices of their time and are only handed down in fragments.

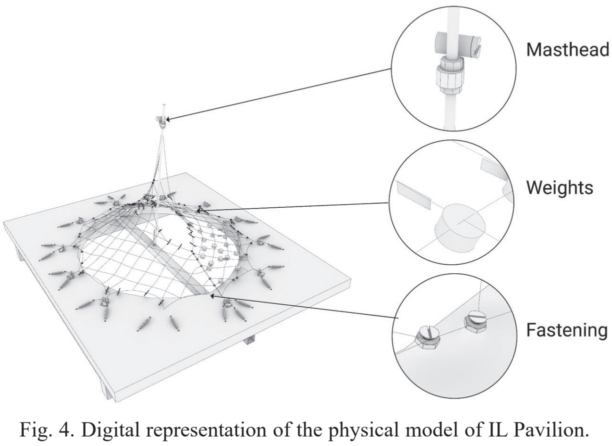

Fig. 4. Digital representation of the physical model of IL Pavilion. It consists of very thin spring steel wire, which is difficult to capture using conventional recording methods (drawing by B. Wenzel, J. Nett)

Il. 4. Cyfrowa reprezentacja fizycznego modelu Pawilonu IL. Składa się z bardzo cienkiego stalowego drutu sprężynowego, który trudno uchwycić za pomocą konwencjonalnych metod rejestrowania (rys. B. Wenzel, J. Nett)

Retrodigitisation/retro-engineering of the surviving physical models – methods

Digital representations of these physical models were created as part of our project "Last Witnesses" as a basis for further scientific research into these objects of transition. We have carried out a retro-digitisation of these objects like the model for the IL pavilion (Schmid, Weber 2021; Wenzel et al. 2021) (Fig. 4). The mast and cable-roof construction were in early 1967 a 1:1 testing model for the German Pavilion at the EXPO67 in Montreal, designed by Rolf Gutbrod (1910–1999), Fritz Leonhardt, and Frei Otto.

The construction of this mock-up was later translocated and became Frei Otto's institute, *Institut für Leichte Flächentragwerke* (IL) (Weber 2011, 68–83; Kleinmanns et al. 2020). We refer to these retro-digitised models as digital twins, although we are aware that this term has a somewhat broader meaning in the mechanical engineering: the concept of *digital twins* in general drove the digitisation of industrial product development because it consequently avoids costly and time-consuming material testing, mock-ups and prototypes (like the IL Pavilion at its time). Digital twins help to simulate and predict the present and future behaviour of a physical object, which in turn allows for

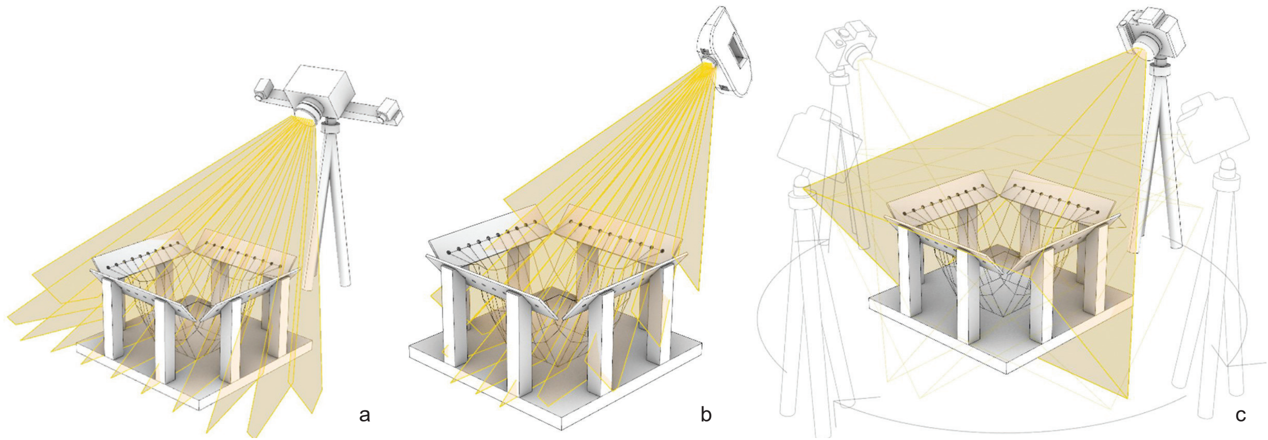

Fig. 5. Diagrams of function from retrodigitization tools, which were tested for their suitability for the thin wires (up to 0.8 mm): a) structured light scanner, b) LIDAR scanner, c) photogrammetry (drawing by B. Wenzel)

Il. 5. Schematy funkcjonowania narzędzi retrodigitalizacji, które zostały przetestowane pod kątem ich przydatności do cienkich drutów (do 0,8 mm): a) skaner światła strukturalnego, b) skaner LIDAR, c) fotogrametria (rys. B. Wenzel)

object optimisation and to offer variants easily, altogether improving business efficiency and hopefully sustainability. While the term and procedure are standard in industrial product development, with aerospace and automotive industries being forerunners, there are up to now only few known applications for the architecture and engineering sector. Industry 4.0 offers important orientation to the construction industry in dealing with digital planning and management. Comprehensive networking of data sources and the coupling of simulation models are increasingly important for building processes such as BIM and integrative computational design and construction[2].

The digital representations of the surviving physical models in the "Last Witnesses" project were created using state-of-the-art digital tools. Algorithms as well as different modelling programmes were tested for their applicability. There are two different methods of reversed engineering available and both have been tested for the generation of digital twins:

A. By using the structured light 3D scan, a 3D meshface is computed by projecting a simple stripe pattern on the object. The degree of distortion is measured by comparing the projected stripes with detected stripes, which allows the calculation of the relevant information about depth. Evaluation of the depth applies for all correspondences with respect to the focal points of the camera. The result is a cloud of 3D points.

B. By using 3D laser scan, the scanner emits a laser beam, which results in reflections from the surroundings, and these reflections are received by the optics. In this case, a rotating mirror deflects the beam and the laser light received by the scanner is evaluated accordingly and again results in a cloud of 3D points.

Both methods were tested on a representative replica of a cable net model, but neither provided satisfactory results. The difficulties in collecting data for reverse engineering are the often very thin wires or transparent or translucent components like acrylic plastics or glass fibre-reinforced plastics, which formed the physical models of lightweight constructions and shells.

These objects are hard to recognise by laser technologies, so it was necessary to turn to the most time-consuming method, photogrammetry, which is manual, but most of the time leads to the best results (Fig. 6). For the photogrammetric method, an object is first recorded with a camera from various angles. Every externally visible point must be clearly visible in at least two photos. By using at least two corresponding image points from two different recording positions, if the mutual position is known, the two rays can be brought to intersection and each object point can be calculated three-dimensionally.

Therefore, the process of retro-digitization usually begins by taking photographs of the model with a digital single-lens reflex camera. In the next step, the results serve as the basis for the extraction of relevant 3D points with PhotoModeler. In order to make this possible, the photos have to be referenced using target points and an overlap of the images is calculated. Then, the program Rhinoceros3D is used to scale the geometry and align the extracted points in a global coordinate system. Grasshopper3D allowed the authors to automate the creation of different parts of the models. Kangaroo2 (a particle-based live physics engine) enabled the simulation of elastic models' conditions. Some effort was spent to connect Grasshopper with a database for the models, via a Plug-In written in C#.

For the retro-digitisation of more solid types of models, like a large 1:5 model of a reactor container made of steel, which belongs to Leipzig University, the laser technique (B) was combined with photogrammetry (Fig. 7). The 5-meter-tall object was photographed by a drone.

Use and benefits of retro-digitised data

Today's structural analysis programs allow for much more freedom when planning digital models. You can assign

[2] For the Stuttgart based cluster of excellence on Integrative Computational Design and Construction for Architecture see https://www.intcdc.uni-stuttgart.de/

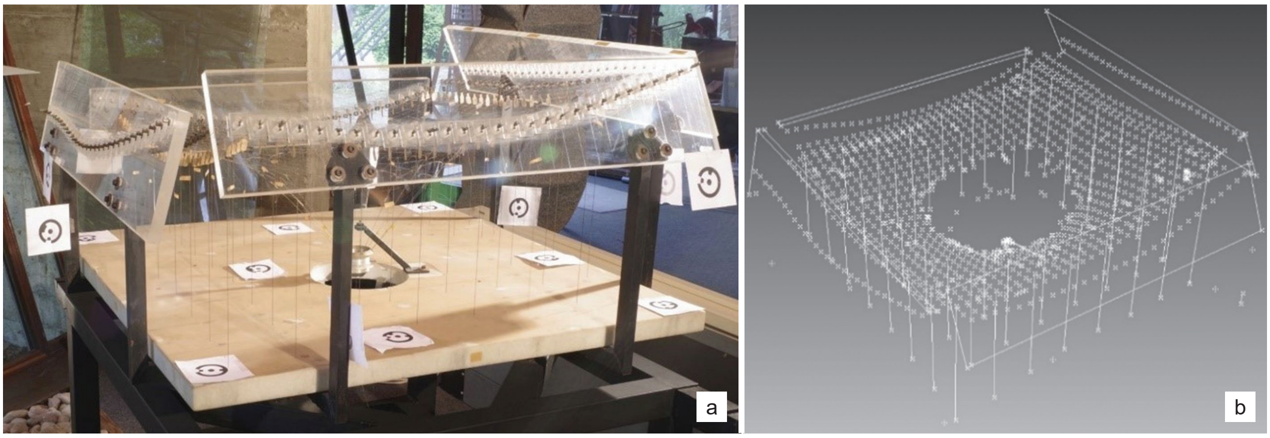

Fig. 6. Surviving model and its cloud of digital 3D Points: a) low point T2 physical model of the Munich Olympia Park Swimming Pool, b) points extracted by using photogrammetry (photo and drawing by F. Brauner)

Il. 6. Zachowany model i odpowiadająca mu chmura punktów: a) model fizyczny T2 niskiego punktu basenu w monachijskim Parku Olimpijskim, b) punkty wyodrębnione za pomocą fotogrametrii (fot. i rys. F. Brauner)

Fig. 7. 3D-Scan of a surviving model and its 3D-Resinprint:
a) for the reactor containment model state of the art tools like drones and terrestrial laser-scanners were used. This model is represented by a polygon-mesh with 220355 vertices and 309975 faces and is fully textured,
b) the same model as a 3D resin print for an exhibition
(drawing and 3D prints by B. Wenzel)

Il. 7. Skan 3D zachowanego modelu i jego wydruk trójwymiarowy:
a) do modelu obudowy reaktora wykorzystano najnowocześniejsze narzędzia, takie jak drony i naziemne skanery laserowe. Model ten jest reprezentowany przez siatkę wielokątów z 220355 wierzchołkami i 309975 ścianami i jest w pełni teksturowany,
b) ten sam model jako wydruk 3D z żywicy na wystawę (rys. B. Wenzel)

any existing material and even create materials with properties that did not previously exist. In most cases, columns, beams and other elements are only available as lines, to which properties such as material and diameter are assigned. Discretised models usually only visualise the diameters of the supporting elements. The surface properties are generally not important and therefore omitted for the sake of the simplification, as described at the beginning. When it comes to such matters of surfaces and external appearance, there are already AI-supported tools that automatically assign UV maps to models. Work that a few months ago had to be done laboriously by hand can now be done by an AI in just a few moments, if you enter the right prompt. The associated polygon meshes are also partly generated by text prompts. We can therefore assume that very soon AI will create a structural analysis model and its calculations.

So, the thus produced digital representations Will serve as a basis for further scientific processing in disciplines such as restoration science, architectural history and civil engineering. Concerning restoration and conservation, the digital model helps to document the materiality and surface quality, including signs of use, and offers possibilities for damage mapping to provide a valuable basis for the restoration process (Fig. 8). The digital twin of the retrodigitised object can be developed as an annotation tool, useful for recording archival sources as well as the documentation of the restoration process by integrating the reports or photos. In this regard the further development of retro-digitisation presents us with the same challenges as HBIM methods, where the aim is to store information on damage, changes, and sources for historical buildings in a BIM model.

From an engineering and mechanical perspective, static simulations, and calculations of structural parameters for changing conditions (caused, e.g., by climate change, such as greater amounts of precipitation and increased snow loads or wind effects) could be simulated and evaluated. The influence of increasing precipitation could for example be tested on the digital twin of the Munich Olympic Sports Hall (Fig. 9) (Wenzel et al. 2021).

One research perspective is the digital reconstruction of the lost test facilities. With the help of virtual animations, the mechanical testing process of the physical model can be visualised as a lost practice of civil engineering. For example, Frei Otto's suspended model for the *Multihalle Mannheim*, which makes use of the reverse principle, currently kept in the German Architecture Museum in Frankfurt (Fig. 10).

Like their material brothers, the digital models store knowledge, carrying information about an innovation-producing lost engineering practice and about how this information was communicated and transferred into building practice. Within the research project, for archival and conservation purposes, data contained in the digital twins is the basis for cataloguing and categorising the objects. A follow-up project intends to store the model-data in an open database according to principles of FAIR for an interested public. In the future, a constantly expanding database of digital models should be made accessible in virtual spaces, for example for academic institutions or museums, to make the objects virtually tangible by using augmented reality.

Conclusion

When the applicants asked for funding in 2019, the expectations to find *more last witnesses* of physical testing models and measurement models from construction and engineering were high. We assumed that there might well be larger numbers of unknown objects. As an open call which led to very poor responses, we had to revise

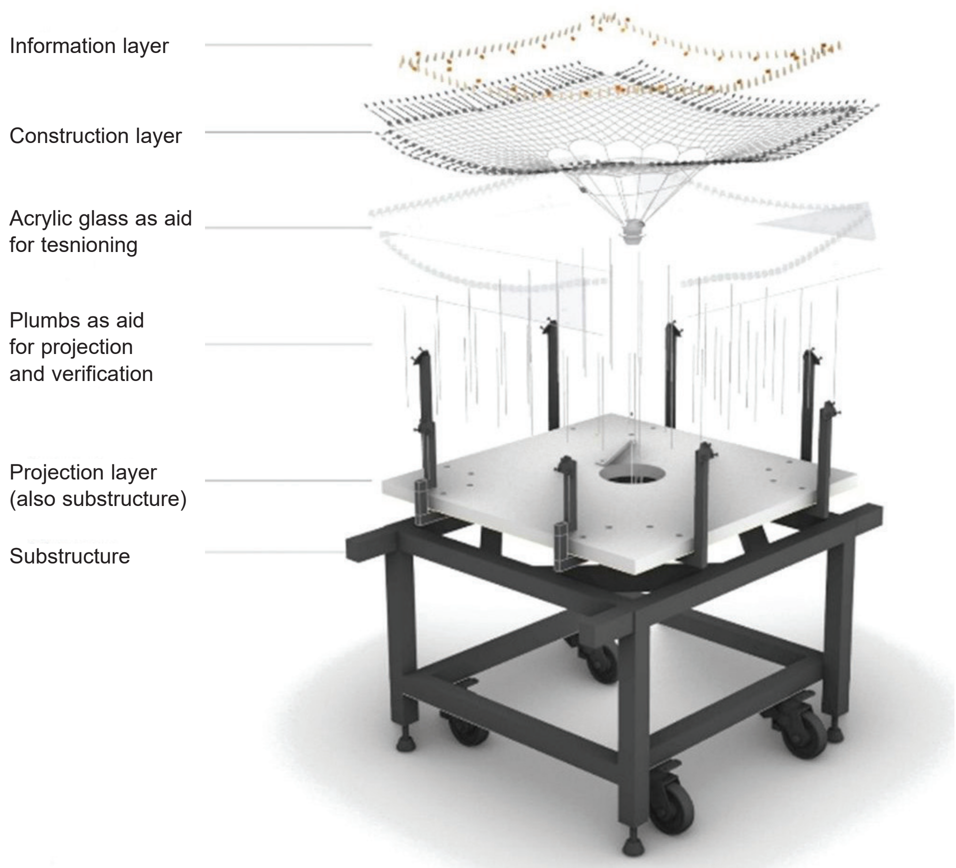

Fig. 8. Damage mapping for restoration purposes as exemplified in the lowpoint model T2 (see: Fig. 6) for the Munich Olympic stadium (drawing by F. Brauner)

Il. 8. Mapowanie uszkodzeń na potrzeby renowacji, jak pokazano na przykładzie modelu punktu najniższego T2 (por. rys. 6) dla Stadionu Olimpijskiego w Monachium (rys. F. Brauner)

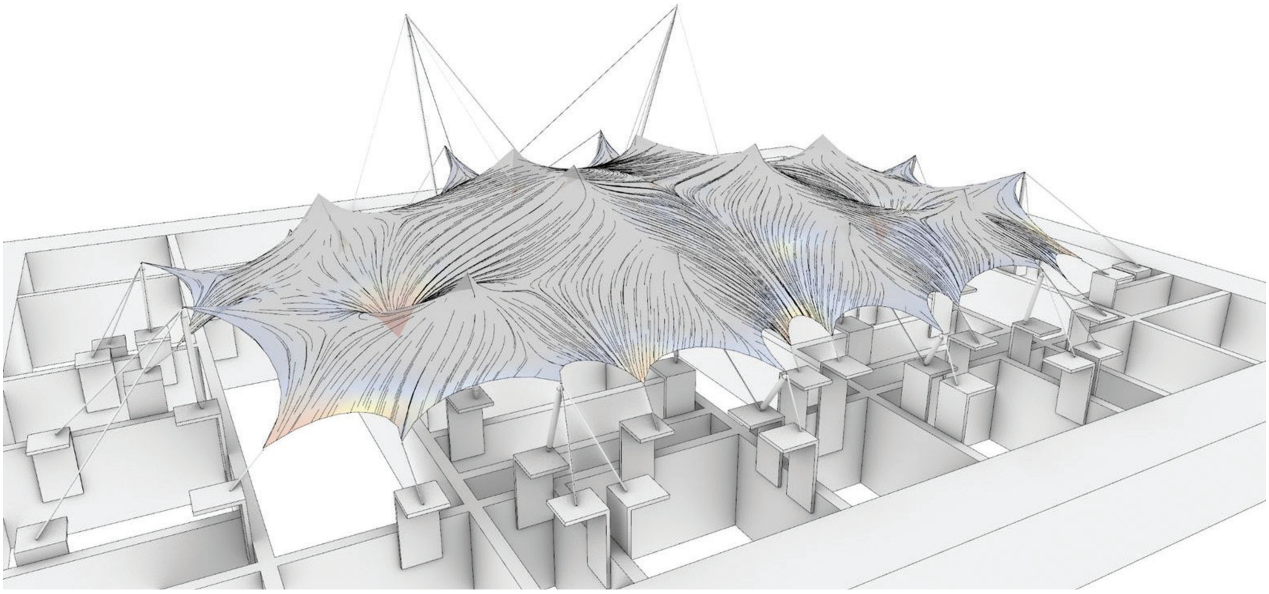

Fig. 9. The digital twin of the measurement model of the Olympic Park sports hall in Munich in use for a qualitative rainwater runoff analysis algorithm on the polygonmesh created by photogrammetry and a physics based particle spring system (drawing by B. Wenzel)

Il. 9. Cyfrowy bliźniak modelu pomiarowego hali sportowej w Parku Olimpijskim w Monachium używany do algorytmu analizy jakościowego odpływu wody deszczowej na siatce wielokątnej utworzonej za pomocą fotogrametrii i opartego na fizyce układu sprężyn cząsteczkowych (rys. B. Wenzel)

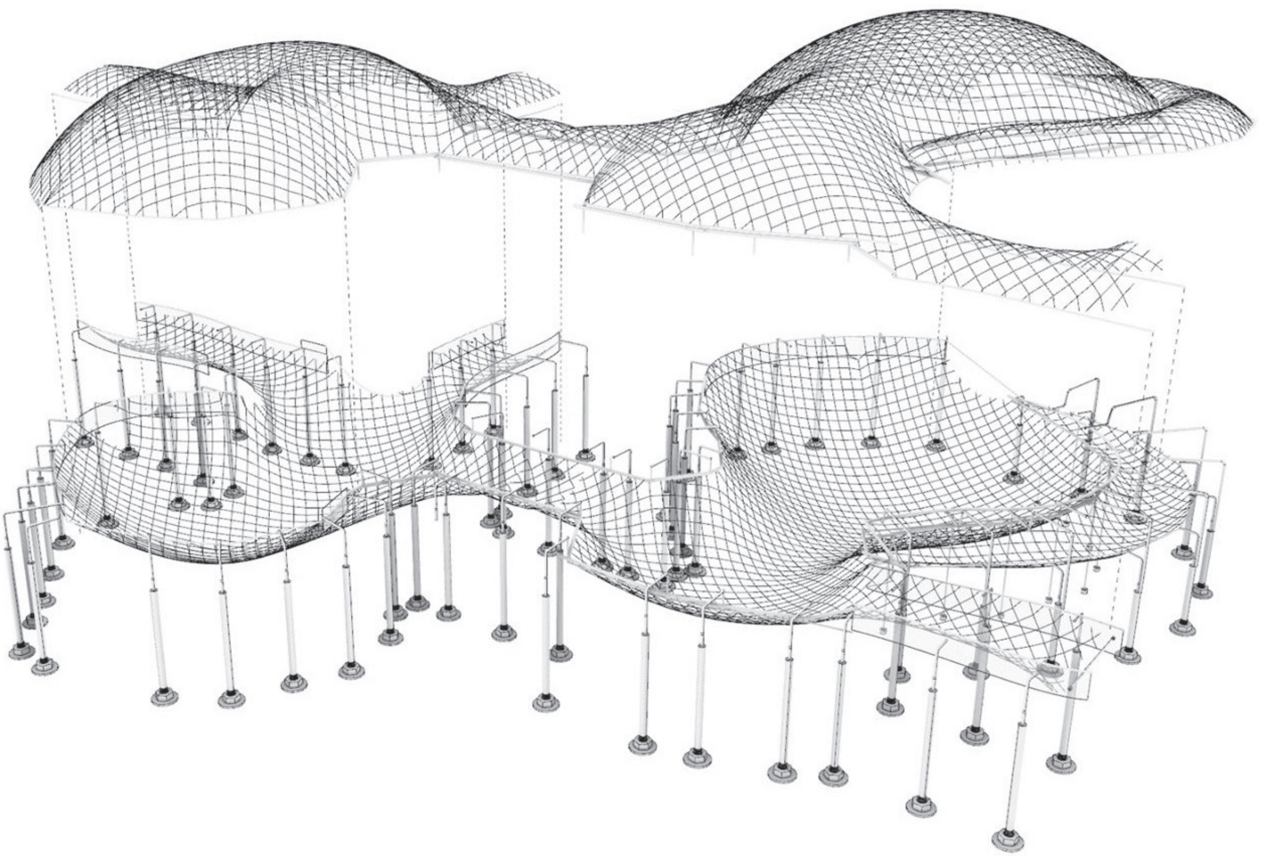

Fig. 10. Digital model of the physical model of Multihalle Mannheim: The so-called inversion principle (below) was applied to the load-bearing structures subjected to compression (drawing by B. Wenzel)

Il. 10. Cyfrowy model fizycznego modelu hali widowiskowej Multihalle Mannheim: Do konstrukcji nośnych poddanych ściskaniu zastosowano tzw. zasadę inwersji (poniżej) (rys. B. Wenzel) our assumption: for German-speaking countries, no more than a dozen physical models could be identified. At the same time, the aesthetic, technical and techno-historical estimation and our construction knowledge of the rare surviving objects has grown immensely. The reasons why the age of model statics came to an end in the 1970s could be clarified and the models that fall into this transition phase could be examined for traces of the beginning automated technology.

For these few "surviving witnesses", matters of restoration and conservation concepts became even more important and resulted in an ongoing campaign to save and valorise the remaining models and model-fragments of outstanding scientific as well as public interest. For this purpose, the digital representations of the models had to be created specifically, which led us to develop methods for the production of digital models, exploring and assessing methods from other disciplines such as geodesy. It is noteworthy, that techniques from the days of early lightweight constructions like photogrammetric approaches still proved the most reliable method for our project, albeit now done with digital cameras and eventually semi-automated. This transfer of established methods from geodesy in architecture to smaller-scale objects also opens up further research perspectives and concepts for their future preservation considering scientific purposes in teaching and experimentation by exploring an integrative AI environment for example, to reconstruct destroyed or no longer preserved models and their testing environment on the basis of photographic and text-based records.

Our aim is an evaluation that focuses on developing concepts for their future preservation considering scientific purposes in teaching and experimentation even more as the last witnesses of model statics allow us to re-engage with past ingenuity and cultures of evidence, which in turn may foster nowadays approaches (Bühler, Weber 2021).

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Streszczenie

Retrodigitalizacja nieeuklidesowych modeli fizycznych w historii budownictwa. Wyzwania, efekty i możliwości

Obecnie dostępnych jest wiele metod tworzenia modeli cyfrowych do dokumentowania, badania lub dalszego rozwoju budynków. Sprzęt i inne technologie zostały przejęte z innych dyscyplin, takich jak geodezja, i są dalej rozwijane specjalnie dla branży budowlanej. Dlatego też metody te mają bardzo konkretny cel i ich zastosowanie jest ograniczone przy zmianie głównego obszaru zastosowań. W ramach projektu badawczego „Ostatni świadkowie

– modele fizyczne w budownictwie lądowym" finansowanego przez Niemiecką Fundację Badawczą (DFG SPP 2255) podjęto próbę przeniesienia znanych metod retrodigitalizacji z architektury na obiekty o mniejszej skali w celu stworzenia reprezentacji cyfrowych. Te obiekty o małej skali to tak zwane modele fizyczne (Messmodelle), szczególny typ modelu stosowany w przeszłości głównie w inżynierii lądowej do testowania konstrukcji nośnych. Modele te były używane w XX w. do obliczania zachowania złożonych konstrukcji, jednak zarówno tworzenie modelu, jak i obliczenia matematyczne były bardzo czasochłonne i podatne na błędy. Od lat 60. i 70. XX w. zostały one zastąpione przez pierwsze wydajne komputery w branży budowlanej.

W artykule omówiono szczególne cechy tych modeli fizycznych i powody, dla których zostały zastąpione komputerami. Opisano przydatność różnych nieniszczących metod retrodigitalizacji i zanalizowano zalety i wady skanowania 3D światłem strukturalnym, skanowania laserowego 3D i fotogrametrii. W kolejnym kroku zademonstrowano potencjał wytworzonych cyfrowych bliźniaków w różnych kontekstach, takich jak renowacja, inżynieria lub historia architektury.

Słowa kluczowe: architektura, modele fizyczne, inżynieria odwrotna, cyfrowy bliźniak, przechowywanie danych

Appendix
Table of surviving and documented measurement models* (elaborated by authors based on Addis 2021)

Aneks
Tabela zachowanych i opracowanych modeli pomiarowych (oprac. autorzy na podstawie Addis 2021)

Object	Time	Page
Technische Hochschule München Tonnenflechtwerk	1895	274 f.
Gebäude 23 Zeiss Süd Jena	1924	276 f.
Schott Dome	1924	275 f.
Dywidagschale Bootsbauhalle Düsseldorf	1925	278 f.
Zylindrische Dywidagschale 1/2	1925	279 f.
Zylindrische Dywidagschale 2/2	1925	280 f.
Markthalle Frankfurt	1927	282 f.
Markthalle Leipzig Kuppel	1927	285 f.
Markthalle Leipzig Kellerdecke	1927	286 f.
Markthalle Budapest Schale	1930	287 f.
Markthalle Budapest Träger	1930	288
Kuppelartige Dywidag Schale (Markthalle Dresden)	1931	289 ff.
Beton Hangars Orvieto, Orbetello, Torre del Lago 1/2	1935–1936	306 f.
Beton Hangars Orvieto, Orbetello, Torre del Lago 2/2	1938–1939	308
Pavillon Messe Mailand	1947	–
E42 Bogen Weltausstellung Rom	1939	310 f.
Kragarmplatte Hospital Clinico Universität Madrid	1929	324 ff.
Innenhofüberdachung Escuela elemental de trabajo	1934	326 f.
Hipodromo de la Zarzuela / Überdachung Tribüne Pferderennbahn Madrid	1935	347 f.
Oberlicht Operationssäle Hospital Clinico Universtität Madrid	1935	329 f.
Markthalle Algeciras Spanien	1934	330 ff.
Frontan Recoletos Madrid	1935	333 ff.
White River Brücke Lake Taneycomo	1931	402
Yadkin River Brücke Albermale und Nount Gilead	–	402
Ashtabula River	1927	402
Bahn Brücke Weikersheim		402
Rheinbrücke Köln-Rodenkirchen	1939	416
Elbbrücke Hamburg	–	417
Druckring Kuppel München Hauptbahnhof	1940	420
Kuppel München Hauptbahnhof	1940	418 ff.
Rheinbrücke Emmerich	1961	420 f.
Alsterschwimmhalle	late 1960s	422 ff.
Deutscher Pavillon Montreal Expo 67'	late 1960s	427 ff.
Olympia Stadion München	late 1960s	431 ff.
King Abdul Aziz Sporthalle Jeddah	1981	435
Pirelli Hochhaus Mailand	1955	449 ff.
Boden Galfa Hochhaus Mailand	1958	452
Stütze Velasca Hochhaus Mailand	1956	45

Table of surviving and documented measurement models (based on Addis 2021)

Object	Time	Page
Bodenplatte Velasca Hochhaus Mailand	–	452
Börsenhochhaus Place Victoria Montreal	1962	452 ff.
Parque Central Hochhaus Caracas Venezuela	1969	460 f.
St. Mary's Kathedrale San Francisco 1/3	1965	461 ff.
St. Mary's Kathedrale San Francisco 2/3	1965	461 ff.
St. Mary's Kathedrale San Francisco 3/3	1965	461 ff.
St. Mary's Kathedrale Tokyo	ca. 1964	462
Australia Square Hochhaus Sydney	1964–1965	462
MLC Centre Hochhaus Sydney	ca. 1972	462
SCOPE Cultural and Convention Center Norfolk	1967	462
Hyperbolische Paraboloidelemente Dach Newark International Airport New Jersey	1968–1969	462
Rupert C. Thompson Arena Dartmouth College New Hampshire	1970–1971	462 f.
Mole Antonelliana Turin	1955	465 f.
Brückendeck Lake Maracaibo Venezuela / Brückendeck General-Rafael-Urdaneta-Brücke Venezuela	1958	465 ff.
Brückenpfeiler Polcevera Brücke Genua	1962	466 f.
Fahrbahn Eisenbahnbrücke Venedig	1963	466
Brücke Basento Potenza 1/4	1967–1975	466 ff. + 589 ff.
Brücke Basento Potenza 2/4	–	467 f. + 589 ff.
Zarate-Brazo Lago Brücke Argentinien	1971	467 f.
Kirchendach Xeralli Pyrenäen	–	482 f.
Schalendach für National Automotive Company ENASA	–	484 f.
Dach Kirche Sant Felix und Ragula Zürich 1/3	1949	485 ff.
Dach Kirche Sant Felix und Ragula Zürich 2/3	1949	485 ff.
Dach Kirche Sant Felix und Ragula Zürich 3/3	1949	485 ff.
Experimentelles Fertigteil-Schalendach	1949	487 ff.
Lagerhaus Fabrik Nadam Havenwerke	1956	491 ff.
Mensadach Universidad Laboral Tarragona Campus	1956	493 f.
Club Tachira Complex Caracas	1957	494 f.
Bürodach Barcadi Havana	1959	498 ff.
Kirche La Paz Barcelona	1961	500 f.
Canadrome Madrid 1/2	1961	502 ff.
Canadrome Madrid 2/2	1961	503 ff.
Palau Blaugrana Sportstadion Barcelona	1970s	505 f.
Strassenbrücke 1954 C&CA	1954	514 f.
Fleet Brücke Hampshire	1954	514 f.
Clifton Brücke Nottingham	1954	517 ff.
Auto Showroomdach Lincolnshire Motor Company	1958	520 ff.
Texas Instruments Factory Bedford	1959	522
Dach Commonwealth Institut London	1959–1960	522 f.
Dach Smithfield Poultry Markthalle London	1960–1961	523 f.
Medway Viadukts	1959	526 f.
Hammersmith Überführung Hochstrasse London	1959	526 ff.
Huntley's Point Overpass Glasesdale Australia	1961	528
Dach Sydney Opera House	1962	529
Metropolitan Kathedrale Liverpool	1961–1964	529 ff.
Cumberland Basin Viadukt Bristol	1962	531 ff.
Mancunian Way	1963–1964	534 f.
Tinsley Viaduct M1 Sheffield	1964	536 f.
West Way London 1/2	1965	537 f.
West Way London 2/2	1965	537 f.

Table of surviving and documented measurement models (based on Addis 2021)

Object	Time	Page
CEGB Cooling Tower	1965–1968	538 f.
West Gate Bridge Melbourne Australien	1967	539 f.
Gateshead Viadukt A1	1967–1970	540
Erhöhter Abschnitt M11 London Cambridge Autobahn	1970–1971	540
Vischer Haus Elsass	1960	553 f.
Holz Pavillon nahe Basel	1959	553 ff.
Bruder Klaus Kirche St. Gallen Schweiz	1957	554 f.
Lagerhaus Verband Schweizerische Konsumvereine Wangen bei Olten	1958–1961	555 f.
Überdachung Lesesaal der Universitätsbibliothek Basel	1964	557 f.
Dach Stadttheater Basel	1968	557 ff.
Kiessilos Günzgen Solothurn	1960	560 f.
Brückenübergang Köhlbrandbrücke	–	560 f.
Pavillon Kern-Element Expo'64 Lausanne	1964	561 f.
Pavillon Element Expo'64 Lausanne	1964	561 ff.
National Westminster Tower London	1971	566
Brücke Basento Potenza 3/4	–	467 f. + 589 ff.
Brücke Basento Potenza 4/4	–	467 f. + 589 ff.
Bellinzona Schale	1964	620 f.
Museum Dübendorf bei Zürich	–	623 f.
Dach Konzerthalle Hotel Kreuz Langenthal	1954–1955	625 f.
Heilig Geist Kirche Lommiswol bei Solothurn	1967	626 f.
Dach Sicli SA Fabrik Genf	1968	627 f.
Dach Gips Union Bex	1968	626 ff.
Essener Gitterschale 1/2	1962	639 f.
Essener Gitterschale 2/2	–	648 ff.
Multihalle Mannheim 2/3	–	652 f.
Multihalle Mannheim 3/3	1976	656 f.
Olympia Halle München	late 1960s	1036 f.
Neue Kleiner-Belt-Brücke	1964	1036 f.
IL Pavillon	1966	426 ff.
Multihalle Mannheim 1/3	–	641 ff.
Müther Schale Sport- und Kongresshalle Rostock	1970	–
Stadtzentrum Tucuman	1949	314 ff.
Tiefpunkt T2	late 1960s	–
Reaktor Containment Leipzig	early 1980s	–

* All models mentioned in this article are underlined.