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RESEARCH

Rooted in Nature: Aesthetics, Geometry and Structure in the Shells of Heinz Isler

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Abstract Reinforced concrete shells frequently constitute the most visible element of a building envelope. They dominate the architectural expression, yet the three-dimensional form is generally determined by the engineer according to its structural efficiency, rather than by the architect according to aesthetical considerations. This raises the question "Who is the author of the design?" The design philosophy of recognised shell designers is introduced, specifically that of Swiss shell designer and "structural artist" Heinz Isler, who is considered to have had particular sensitivity to the aesthetics of his shells, rooted in his admiration of the natural world and derived by natural laws. The Sicli Factory shell, 1968, is taken as a case study and is used to compare Isler's design method with contemporary digital form-finding using the particle spring method. It is concluded that there are advantages and disadvantages to both physical and digital modelling methods. Designers should be encouraged to explore with various approaches.

Keywords Heinz Isler · Aesthetics of reinforced concrete shells · Sicli SA · Hanging cloth reversed · Particle spring system

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Introduction

The design of graceful shell structures requires a complex interaction of aesthetics, structure and mathematics. Close collaboration between architect and engineer is essential to deliver an elegant and efficient form. This raises the question: "who is the author of the design?" In some instances, the person responsible for the engineering design is more widely recognised than the project architect. Possibly this is because the shell designer has aesthetic discernment to complement their engineering design skill, allowing them to fully exploit the formal possibilities of their chosen material. Such discerning shell designers include Eduardo Torroja y Miret (1899–1961), Pier Luigi Nervi (1891–1979), Félix Candela (1910–1997) and Heinz Isler (1926–2009).

Eduardo Torroja y Miret (1899–1961)

Eduardo Torroja y Miret was a Spanish engineer and pioneer of reinforced concrete thin shell construction. His works included: a 90 mm thick, 47.5 m diameter spherical domed shell for the *Market Hall*, Algeciras, Spain (1933); a 32.5 m span double barrel vault for the *Frontón Recoletos*, in Madrid (1935); and 13 m long cantilevered canopies, 60–145 mm thick, at the *Zarzuela Hippodrome*, Madrid (1935) (Fig. 1). These shells had simple geometries that could be calculated relatively easily by hand (the only method available at the time): a segment of a sphere, parallel extruded arches, and linked hyperbolic paraboloids. Torroja's concern for the elegance of his structures is demonstrated by a chapter devoted to 'The Beauty of Structures' in his book *Philosophy of Structures* (Torroja 1958).

Fig. 1 Hyperbolic paraboloid shells, Zarzuela Hippodrome, Madrid, 1935 (Photo: John Chilton)

Pier Luigi Nervi (1891–1979)

The Italian engineer Pier Luigi Nervi was noted for his use of "ferro-cement", thin elements made from fine aggregate concrete applied to a fine reinforcement mesh. These he used as permanent formwork for the economical production of beautiful ribbed and coffered shells. One of his most elegant shells, for the *Palazetto dello Sport* (Small Sports Palace), completed in 1957 for the 1960 Rome Olympics with architect Annibale Vitellozzi, has rippling edge stiffening to reduce the shell thickness (Fig. 2). The gracefulness of Nervi's structures, his ambition to create beautiful objects, and his mastery of reinforced concrete as a sculptural material—described in his book *Aesthetics and Technology in Building* (Nervi 1966)—led to him receiving the Royal Institute of British Architects (RIBA) Gold Medal in 1960.

Félix Candela Outeriño (1910–1997)

Architecturally trained but acting principally as a constructor (Faber 1963: 10), the Spanish architect Félix Candela is considered the master of thin reinforced concrete shells based on hyperbolic paraboloid (hypar) surfaces produced using straight line generators. Most of his notable works were constructed in Mexico, where he relocated following the Spanish Civil War, subsequently establishing the construction company Cubiertas Ala S.A. According to Moreyra Garlock and Billington (2008), Candela's favourite examples of his innovative works were the *Iglesia de la Medalla de la Virgen Milagrosa*, (Church of the Medal of the Miraculous Virgin) Narvate (1953–55), comprised of multiple tilted hypar surfaces; *Chapel Lomas de Cuernavaca*, Morelos (1958), a segment cut from a single hypar; *Los Manantiales Restaurant*, Xochimilco (1958), (Fig. 3a), cut from four intersecting hypars; and the *Bacardi Rum Factory*, Cuautitlán (1960).

Discussing Candela's *Cuernavaca Chapel*, Colin Faber comments that "(i)t has been suggested that the free edge is the ultimate refinement of shell design" perhaps because this hints at the shell thickness (or thinness) and develops a more refined

Fig. 2 Internally ribbed shell dome, Palazetto dello Sport, Rome, 1957–59 (Photo: Gabriel Tang)

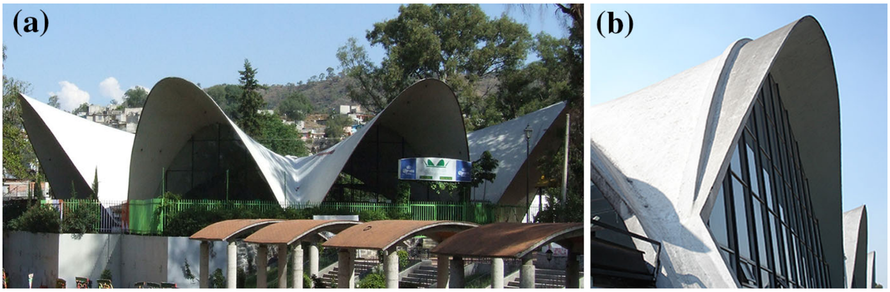


Fig. 3 **a** Los Manantiales Restaurant, Xochimilco, Mexico, 1958—Félix Candela, architectural design Joaquin and Fernando Alvarez; **b** stiffening rib, Bacardi Rum Factory, Cuautitlán (Photos: Marisela Mendoza)

aesthetic. Faber qualifies this, saying that this requires stiffening elements to resist unequilibrated stresses. He reports that Candela "…regards the free edge as the final result of one phase of structural investigation, rather than an indication that the thin shell has been carried to its limits" (Faber 1963: 202). At the *Bacardi Rum Factory*, Candela employed an arch rib positioned slightly behind the free edge for this purpose (Fig. 3b).

The final acknowledged designer is Heinz Isler whose approach to shell design is described in detail in the following section.

Heinz Isler—Structural Artist

In contrast to the shell designers mentioned above, the Swiss engineer Heinz Isler (1926–2009) is remarkable in that he originally intended to follow a career as an artist. At school he had displayed a natural talent for sketching and painting (Fig. 4).

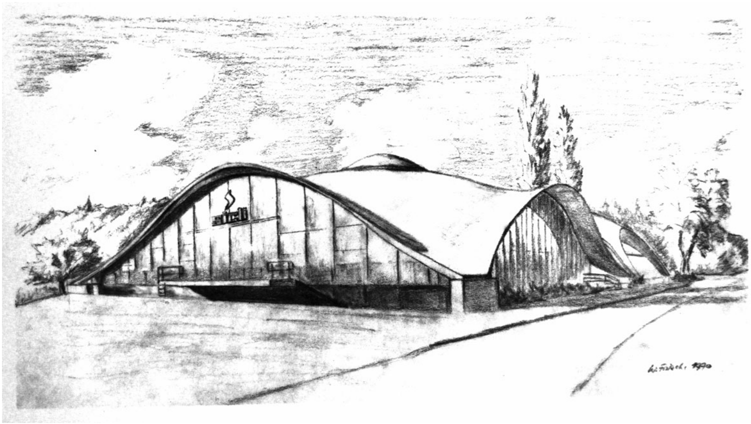


Fig. 4 Pencil sketch of Sicli shell by Heinz Isler (© gta archives/ETH Zurich (Holding Heinz Isler). Photo: Chu-Chun Chuang)

However, his father insisted that he should study for a more secure profession. Hence, after his national service, he enrolled to study civil engineering at the Eidgenössisiche Technische Hochschule (ETH) in Zürich, where his dissertation under the supervision of Pierre Lardy (1903–1958), was on thin reinforced concrete shells (Chilton 2000). After graduation Isler worked as Lardy's assistant until May 1953, when he took a job to fund art studies in Munich. The project he was employed to realise, a shell roof at the *Hotel Kreuz*, Langenthal, diverted him irrevocably from his original course. Nevertheless, he carried his aesthetic sensitivity into his future shell designs, fully justifying the designation "structural artist" (Billington 2003).

In his book *The Art of Structural Design; A Swiss Legacy*, Billington (2003) quotes Isler recalling what his teacher and mentor Lardy had told his engineering students:

> "(a) that we have in us a sense for esthetics, (b) that we have the right to use it, (c) that we are allowed to mention our opinion, (d) and that we can find and express it in our projects" (Billington 2003: 132).

Isler enthusiastically acknowledged Lardy's encouragement "*…to find and apply esthetics from within us*". and believed this to be one of the greatest influences on his professional development. This guidance Isler ultimately expressed through his own designs, in which he balanced the aesthetics of his shells against their structural efficiency.

New Shapes for Shells

Isler's alternative and innovative form-finding methods came indisputably to the attention of his contemporaries at the First Congress of the International Association for Shell Structures, organised by Torroja in Madrid, in 1959. Reinforced concrete shells were widely used at the time but were almost exclusively relatively straightforward forms defined by simple mathematical formulae e.g. barrel vaults, spherical domes, hyperbolic-paraboloids. Isler's paper C3, "New Shapes for Shells", was the last to be presented. Five pages in length, containing fewer than 1000 words but illustrated with nine figures, it proposed three alternative form-finding methods: the freely-shaped hill, the membrane under pressure, and the hanging cloth reversed. He recommended the hanging cloth reversed as the best for form-finding of large shells (Isler 1961; Chilton 2009; Ramm 2011). The paper concluded with a 4 × 10 matrix showing 39 possible shell forms, sketched by Isler, with the remaining cell labelled "etc." to suggest the infinite spectrum of potential forms (Chilton 2010).

Responding to Torroja's comments during the extensive discussion, the Bulletin of IASS (Isler 1961) reported that Isler listed five key aspects of shell design:

- the functional
- the shaping
- the architectural or artistic expression
- the statics
- the others—acoustics, light and so on.

It is unclear whether these were in order of importance, but two did relate to aesthetics. Isler emphasised that for three-dimensional forming of shells one needs to utilise methods that are not limited to the flat drawing board. Instead, Isler championed free modelling as practised by artists, making the point that three-dimensional problems can best be solved through physical analogies, such as membranes or soap skins (Isler 1961; Chilton 2009). His comment is still pertinent today with respect to the dominance of the flat, two-dimensional computer screen—instead of the drawing board—in three-dimensional form design. However, contemporary digital fabrication technologies, like rapid-prototyping and 3D-printing, provide the opportunity to rapidly generate multiple physical models from digital data.

Influence of Félix Candela

Isler acknowledged the influence that Candela's shells had on his work. In the early 1960s, he encountered a book featuring Candela's shell roof for the *Los Manantiales Restaurant*, Xochimilco, Mexico (Fig. 3a) on its cover. Isler was captivated by the thinness of that shell (approximately 40 mm at the edge), which emphasises the lightness of the construction and enriches its aesthetic qualities (Billington 2003: 135). In his contribution to the Félix Candela Lecture series, Isler recognised that Candela "…was, for his time, the master builder of shell structures", commenting that the Los Manantiales Restaurant had been the greatest influence on his own development (Isler 2008: 87). He was inspired to match its qualities in his own shells. This provides insight into Isler's awareness of the aesthetic qualities of his designs and his understanding that the perceived weight of the shell depends critically on its apparent thickness, visible at the edge. This perhaps explains Isler's limited enthusiasm for the equilateral triangular spherical segment shells he engineered for sports facilities in Chamonix (1970–1975). There, the structurally inefficient configuration, dictated by the architect Roger Taillibert, required substantial edge beams to maintain stability under heavy design snow loads (Chilton 2000: 86–89). In contrast, Isler's triangular plan shells for the *Deitingen Süd Petrol Station*, form-found as a hanging membrane, have a 90 mm thick free edge (see Fig. 8).

The Hanging Cloth Reversed

During a recorded conversation with Ekkehard Ramm and the first author, at Isler's Lyssachschachen office in 2003, when talking about others trying to emulate the aesthetic qualities of his designs in the future, Isler declared that he had, in his opinion, "…done it about a dozen times successfully". Most of this dozen were designed using the hanging cloth reversed. This preferred method exploits the deformation of a flexible hanging cloth, net or membrane under gravity to generate a surface in pure tension under self-weight. The resulting form, when inverted, is in pure compression under equivalent loading.

With this technique, even when load conditions and support locations are identical, there still exists an infinite number of potential surface forms; for instance, according to type and orientation of the cloth or membrane and area suspended between the supports. Each has the potential to create a pure compression shell under self-weight. Then, respecting the design criteria, listed above, Isler was free to exercise his aesthetic and/or artistic sensitivity to select the most elegant form (Chilton 2012: 3). Effectively, he was undertaking three-dimensional parametric design using physical models. In the first author's final conversation with Isler, by telephone in December 2008, he observed that he just let his structures "become".

Free-form Shells

Although Isler had been experimenting with his hanging cloth form-finding method since 1957, the first structures realised using this technique were a workshop/showroom for Gips Union SA, Bex, and a motorway service station at Deitingen, both in Switzerland and constructed in 1968.

The most widely used Isler free-form shells are the tennis and sports halls. He explored their geometry in depth. Figure 5a shows alternatives with the same plan dimensions. That on the left has the most exaggerated arch, potentially best for tennis hall functional requirements, but has the greatest surface area and uses most material. Vertical support reactions are higher but horizontal reactions lower. Conversely, the form on the right has the lowest rise, perhaps less acceptable functionally, but the smallest surface area using the least material. Vertical reactions are lower but horizontal reactions higher. Three surfaces have an upturned lip at their free edges, assisting in the resistance of local edge buckling, whilst the long edges in the shell on the right turn down. The proportions of the intermediate solutions appear more elegant aesthetically, and are close to those of sports halls in Norwich, UK, constructed in 1987 (Fig. 5b).

Aesthetics of Isler's Shells

Heinz Isler's feeling for the aesthetics of his shells is revealed by his attention to detail. Even his abundant "bubble" shells (Fig. 6)—form-found using an inflated membrane and constructed in their hundreds mainly as roofs of commercial and industrial buildings—include an elegant rounded corner feature. Giving a smooth transition between perimeter beams, the curve minimizes the reverse curvature that would otherwise occur in the shell. It also accommodates anchorages required for pre-stressing used to minimize the size of perimeter beams. The economy and

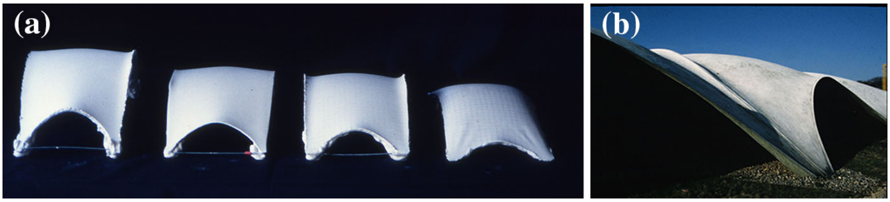


Fig. 5 **a** Alternative inverted membrane tennis and sports hall shell forms; **b** shells at Norwich, UK (Photos: John Chilton)

Fig. 6 Isler's 'bubble' shells with rounded corner detail (Photo: John Chilton)

structural efficiency of these shells is validated by the fact that well over 1000 were constructed, the last one completed in 2009. Kotnik and Schwartz (2011) have suggested that, with the shell form having been derived from natural forces, for Isler, the engineering aspects did not "…constitute the chief concern of the design". Consequently, these shells "…cannot necessarily be regarded as industrial buildings" (Kotnik and Schwartz 2011: 188) and may also be considered as examples of Isler's structural artistry.

Heilig Geist Kirche (Holy Spirit Church), Lommiswil, Switzerland, 1967 (Fig. 7a), is an example of Isler taking the dominant architectural role in the shell design, allowing him to directly apply his aesthetic skills. He proposed the overall rising spiral church form, subsequently adopted by the architect Roland Hanselmann, roofing it with a free-form cut-out from a tilted hypar surface (Chilton 2011).

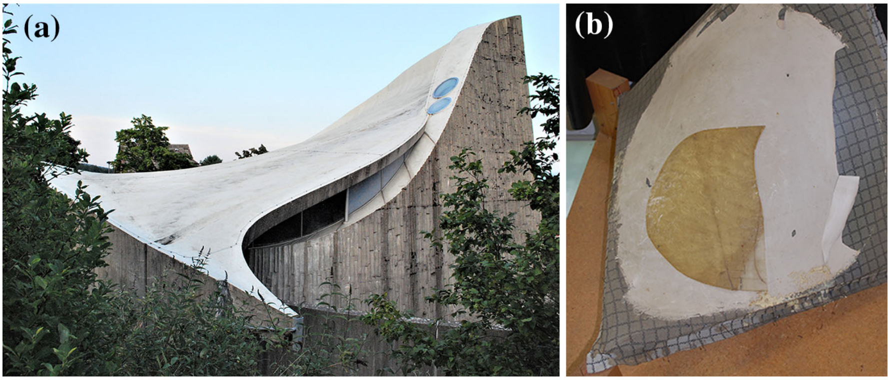


Fig. 7 **a** Heilig Geist Kirche (Holy Spirit Church), Lommiswil, **b** roof segment cut from a hypar surface (Photos: John Chilton)

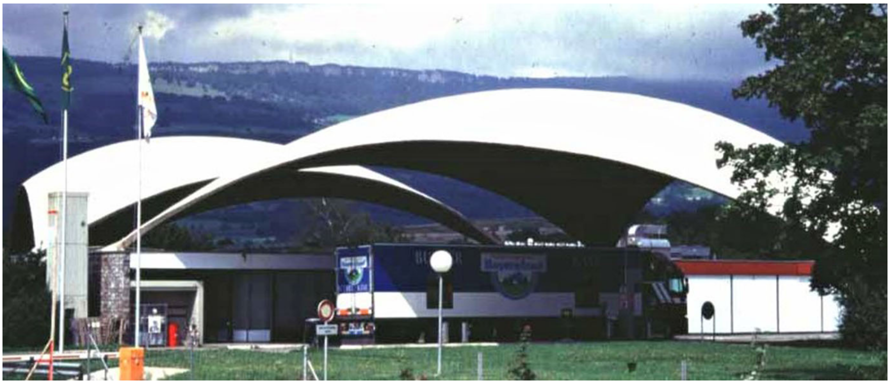


Fig. 8 The 31.6 m span shells for Deitingen Süd Petrol Station (1968) (Photo: John Chilton)

This is one of a few examples of Isler using this mathematically described surface, although he applies it in an innovative architectural configuration (Fig. 7b). A subtly-placed (barely visible) steel prop allows the thickness of the free shell edge to be minimised, Fig. 7a.

For Isler's shells, particularly those form-found by the hanging membrane reversed, there is a tension between the aesthetic experience of the delicate thin shell canopy (relatively thinner than a bird's egg) and the architectural requirement to enclose. A façade connects the shell perimeter to the ground and compromises the perception that the shell is floating above the landscape. It marks a transition between the introverted interior enveloped by the shell and the more open quality engendered by the lightweight appearance of the tapered edge (Kotnik and Schwartz 2011: 189). This rationalises the admiration for Isler's twin 31.6 m span shells for *Deitingen Süd Petrol Station* (1968) (Fig. 8), and the 42 m span *Grötzingen Open Air Theatre* (1977), in collaboration with architect Michael Balz (Fig. 9). The Grötzingen shell, in particular, demonstrates Isler's ideal of a pure aesthetic form, derived by natural laws, displayed in a natural setting and with minimum impact on the environment. It is one of three examples Isler used in a conference presentation on the role of aesthetics in his shell designs, saying that "…its natural shape seems to be part of nature itself" (Isler 1981).

Surface patina contributes to the concrete shell aesthetic. In sympathy with his admiration of the natural world, Isler preferred the external concrete of his shells (an artificial stone) to remain uncoated to acquire a veneer of moss and lichen, as would happen to their natural counterpart.

Case Study: Sicli Shell, Geneva, 1969

David Billington, Emeritus Professor of Civil and Environmental Engineering at Princeton University, has commented:

Fig. 9 The 42 m span shell for Grötzingen Open Air Theatre (1977) (Photo: John Chilton)

> This structure is the most dramatic testimony to date of the inherent potential for thin-shell concrete roofs to be works of structural art. But this can happen only if the architect or owner gives the structural artist full control of the making the form. Very few architects would be willing to do this, and, in fact, the Sicli building came about because the owner asked Isler to make the form and the architect accepted (Billington 2003: 143).

Billington's endorsement stimulated the second author's Masters dissertation study, *Design of Heinz Isler's Free Form Shell Structure: Form-finding for Sicli Factory Shell*, University of Nottingham (2014), on which parts of this section are based.

Overview

One of the most challenging of Isler's completed projects is the former *Sicli SA Factory* shell, erected in Geneva in 1968–1969 and designed in collaboration with architect Constantin Hilberer. Recently converted into the *Pavilion Sicli* cultural centre, the asymmetric shell has seven supports. The original building consisted of a 1100 m^2 fabrication hall and a two-storey administration centre sharing an intermediate outdoor space. Total span of the roof is approximately 33 × 53.5 m, with a larger shell (35 × 30 m) linked to a smaller asymmetric surface with maximum height of approximately 8.75 m (Fig. 10) (Chilton 2009). The shell is generally just 90 mm thick, cast on 50 mm of insulation used as permanent formwork.

Alternative Designs—Solutions A, B and C

Three early design options were found in the Heinz Isler Holding of the gta Archives/ETH Zurich, which contains material recovered from Isler's former design

Fig. 10 Sicli SA Factory shell, Geneva (© gta archives/ETH Zurich (Holding Heinz Isler), Photo: Chu-Chun Chuang)

office. Three solutions (Fig. 11) were sketched in pencil by Isler, on a single sheet, dated 5th July 1967. His brief descriptions are translated as:

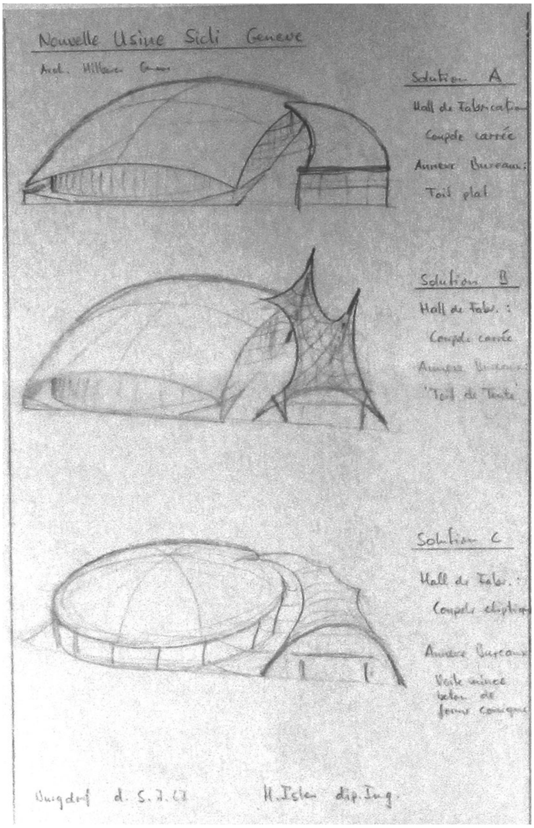
- Solution A: a shell formed square in plan as the main factory with a flat roof for office area
- Solution B: a shell shaped square in plan for the main factory and a tent as the roof for office area
- Solution C: an elliptic shell roof for the main factory and a curved conical thin concrete shell over the office space (Chuang et al. 2016).

Each was composed of a main factory shell linked to a two-storey administration office, enclosed by a separate shell or tensile membrane. Solutions A and B have an approximately square plan on four supports, slightly raised to increase headroom in the factory space. Although an architectural model was produced for solution A, there is no evidence that any of these solutions was pursued from the structural point of view, perhaps because of the uncomfortable aesthetic relationship between the office roof and factory shell.

Free-form Design—Solution D

Distinct from the previous options, solution D (Fig. 12) merged all functions under one single free form, incorporating a glazed atrium with clerestory windows. This was possibly inspired by Isler's interest in natural form—a spiral shell perhaps, which is a beautiful element providing perfect shelter in nature. It was supported at fourteen points, generating a scallop-shaped pattern on the glazed façade. A solid

Fig. 11 Sketches for solutions A, B and C (© gta archives/ETH Zurich (Holding Heinz Isler). Photo: Chu-Chun Chuang)



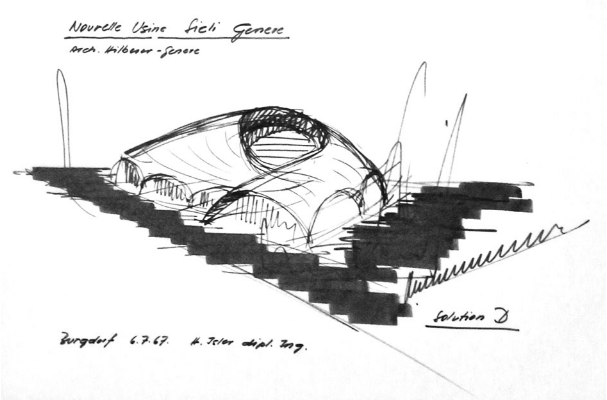


Fig. 12 Sketch for solution D (© gta archives/ETH Zurich (Holding Heinz Isler). Photo: Chu-Chun Chuang)

physical model of this solution was made but there is no evidence that this option was taken further, perhaps because of the challenge of producing the shell surface supported on just the fourteen external points.

Reversed Hanging Membrane Solution

The option chosen for construction resolved all problems encountered in solutions A, B, C and D. This form, derived using the hanging membrane reversed modelling method, shown in Isler's sketch (Fig. 4), is an impressive way to cover two separate architectural spaces of different volume with one single surface. It creates one asymmetric, elegant and structurally efficient surface, whilst providing the maximum area to comply with functional requirements.

For this modelling approach, all details have to be treated with patience and care, using quality modelling materials. Fifteen models, used to define and refine the final shape, were found in the Isler archive. The exploratory models, for example that shown in Fig. 13a, aimed to ensure that stresses were evenly distributed, to minimise deformation and avoid buckling of the surface. Each was an experiment designed to test different configurations, membrane materials (high-quality latex rubber membrane or orthotropic textiles), fabric patterns, thickness of plaster used to apply the load and the scale of the model.

Following accurate measurement of the selected plaster surface, a large-scale resin model (Fig. 13b) was made and load tested to determine stress distribution, deformation and buckling behaviour. This stage of the modelling process allowed Isler to adjust the shell form according to its predicted performance.

Geometry of the Sicli Shell

Little information relating to the detailed geometries of Isler's shells has been published. However, the shell geometry is of importance to assess its structural behaviour and to appreciate the elegance of its form, and by this understanding to realise how a good shell should be formed, especially for a complex geometry like the Sicli shell.

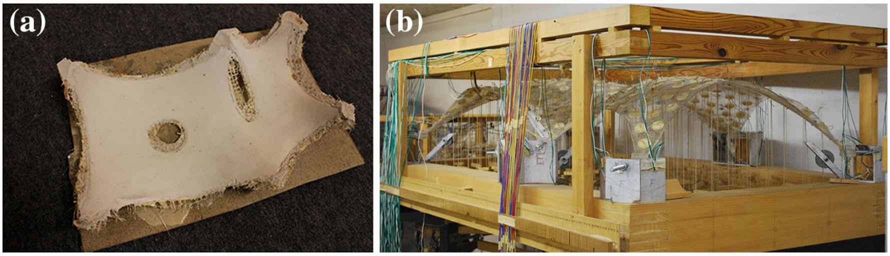


Fig. 13 **a** Physical hanging membrane model of the Sicli shell; **b** resin model used for structural verification (Photos: John Chilton)

Surface Coordinates Measured by Isler

Isler's concept was to produce the full-scale shell geometry by scaling coordinates measured on his preferred physical model. These coordinates were measured precisely to an accuracy of 0.01 mm—using a jig invented by Isler—anticipating the increase in tolerance when scaling up to full size. Nodes were mapped as intersection points of a grid on the shell surface, then the height of each was measured and transcribed. A total of 2100 points were recorded for the Sicli shell and used as setting out points (Fig. 14).

Since the era when Isler was designing his iconic shells, technological advances have provided designers with a range of techniques to measure physical forms, including 3D laser scanning technology (Borgart et al. 2012), which is an accurate and efficient method.

Generating Isler's Measured Surface

To reproduce the Sicli shell in a computer aided design (CAD) environment, the authors used the coordinates of setting out points, found in the gta archive, to generate a point cloud. This was reconstructed as a NURBS (non-uniform rational B-spline) surface (Fig. 15) using Rhinoceros 3D software (McNeel & Associates 2017).

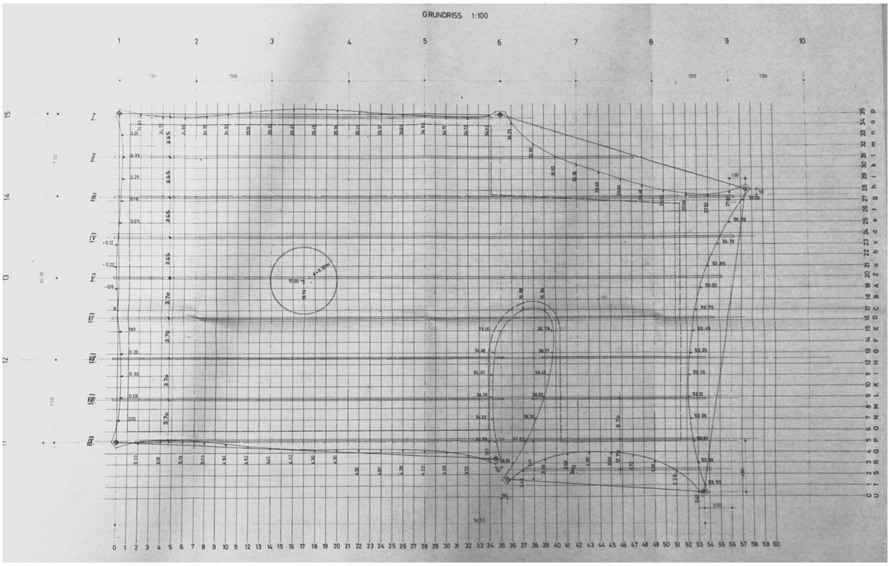


Fig. 14 Setting out point grid for the Sicli shell (© gta archives/ETH Zurich (Holding Heinz Isler). Photo: Chu-Chun Chuang)

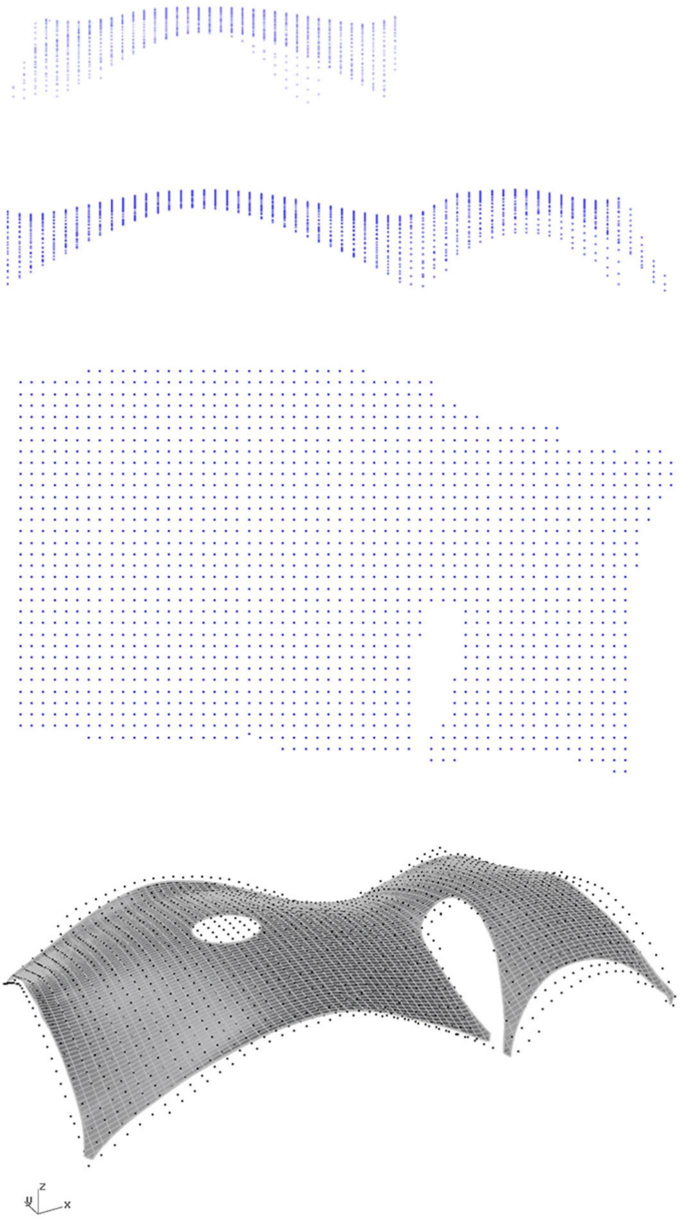


Fig. 15 The 2100-point cloud of the Sicli shell reconstructed in Rhinoceros 3D (Graphic: Chu-Chun Chuang)

Digital Modelling of the Sicli shell

The CAD environment has provided designers with increasing opportunities to achieve high accuracy in the digital modelling process. To what extent can these be integrated into the design of a free-form shell, and how can digital tools help to overcome the limitations of conventional design procedures? In response, the particle spring method was implemented in Grasshopper™, a parametric design tool, to simulate the concept of the hanging membrane reversed modelling approach. The method, used for cloth simulation in computer graphics (Baraff et al. 1998), is based on the concept that, by manipulating the stiffness of linear elastic springs connecting particles representing a membrane surface and the forces on each, it is possible to attain an equilibrium state and by iterative calculation to optimize the form.

Four parameters were modified: initial particle coordinates, spring stiffness, damping and axial forces. Spring stiffness is of importance to prevent surface wrinkles from developing, similar to when fabric is under compression in the physical environment. Damping controls the amount of energy absorbed by the spring as it moves, and can be applied as a coefficient to each spring. This allows a system to settle down eventually to a static equilibrium position (Kilian and Ochsendorf 2005). In simulating Isler's hanging membrane method the acceleration applied to particles is equivalent to gravity. The more particles employed in the digital model, the greater the accuracy of the final surface, however, more processing time is required. Considering the various factors, about 10,000 particles were utilised under different scenarios. The design was simulated in Rhinoceros 3D, using the parametric plug-in tool Grasshopper™ to control the driven factors. The advantage of simulating in CAD is the interactive user interface, where designers can easily control the variable parameters and instantly gain feedback, enabling them to test more possibilities.

The digital modelling procedure used can be summarized, as follows:

1. Define the surface cutting pattern. The hanging models were based on an oversized cutting pattern (Fig. 16a), as this allows for inextensional deformation before straining the membrane (Ramm 2004) and future control of the boundary conditions.
2. Determine the positions and number of supports. Here, seven points at the same height covering the maximum buildable area to define the initial shape of the model before optimization.

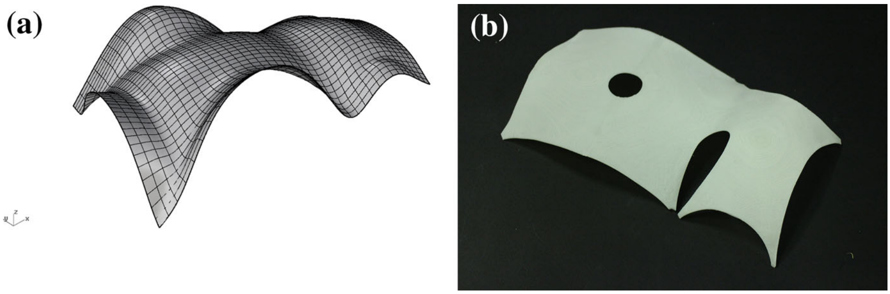


Fig. 16 **a** Oversized NURBS surface to allow inextensional deformation; **b** 3D printed physical model of Sicli shell using Isler's geometry (Graphic and photo: Chu-Chun Chuang)

3. Materialize the surface by defining the discretised pattern. Four patterns, representing different fabric conditions: triangular, orthogonal, diagonal and hexagonal. A hexagonal pattern was chosen to determine the final surface, as it showed a more visually pleasing result.
4. Apply external loading on the surface to derive the enclosure height. The stiffness and weight of nodes is adjusted to find the equilibrium state. This is similar to Isler's physical modelling, i.e. applying a layer of plaster evenly on a membrane and allow gravity to naturally define the optimal shape.
5. Construct a shell with NURBS surface. Once the optimized position of every particle was found, a non-uniform surface was constructed to describe the shape.

The CAD modelling approach aims to save some of the time spent in hanging membrane modelling—what is perceived to be tedious work—by controlling pre-set parameters. Yet, there still remains broad scope for designers to assess alternative solutions by their own aesthetic values. However, Isler always insisted on the benefits of producing physical models to be able to test them physically. This is possibly one of the limitations of the exclusively CAD environment. Ideally, the two design methods should be used to supplement each other. In the CAD environment, rapid-prototyping technologies can now be applied to generate physical models from digitally derived forms, for example, the model of the Sicli shell 3D printed using Isler's geometry (Fig. 16b).

Sample results, shown in Fig. 17, were presumed to be optimized options offering alternative aesthetic possibilities when compared to Isler's physical models.

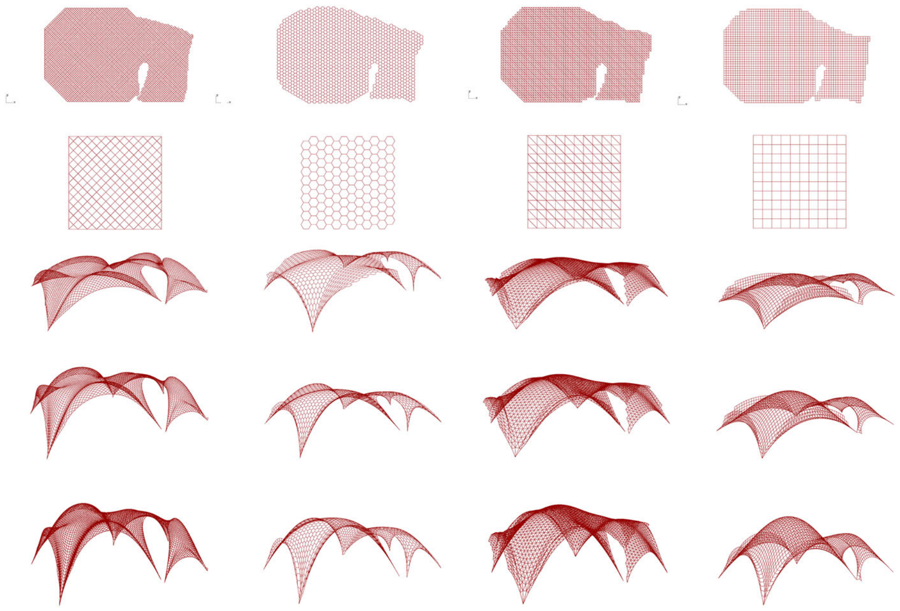


Fig. 17 Digital modelling using different fabric patterns (from left to right: Diagonal: 18,520 particles, 9260 springs; Hexagonal (isometric membrane): 2720 particles, 3995 springs; Orthotropic: 4426 springs, 8924 particles; Triangular, 6725 springs, 13,450 particles) (Graphic: Chu-Chun Chuang)

Nevertheless, the unlimited design options always require the designer's skill, experience and aesthetic judgement to be applied to select the final form.

Comparison of Isler's Shell and Digitally Form-found Geometry

The shape of both models—Isler's produced by physical modelling and the digitally form-found surface derived by the authors using the hexagonal mesh—were evaluated with respect to their aesthetic merits, material efficiency and structural performance. They show relatively similar visual properties, due to both, effectively, having been self-generated whilst having allowed the designers to control various parameters to respect the architectural requirements and the individual's aesthetic values. The most obvious difference is in the edge profiles of the main shell.

The surface area of Isler's shell is about 1480 m^2 and, considering an average thickness of 0.1 m, the approximate material consumption is 148.0 m^3. For the projected plan area of 1440 m^2 this gives an average material usage of 0.102 m^3/m^2. In contrast, the computer-generated geometry requires about 161.7 m^3 of material to cover 1394 m^2 in plan, giving a higher average material usage of 0.159 m^3/m^2.

Finite element analysis (FEA) was applied for evaluation in ANSYS Workbench. Von-Mises stress and total deformation were the criteria used for evaluating structural performance. For simplicity, the shell thickness was assumed to be 100 mm on average, although, in reality, thinner in the middle and thicker near the supports. Material properties used for reinforced concrete were Young's modulus of 30,000 MN/m^2 and Poisson's ratio 0.18. A uniform load of 2000 Pa was applied vertically on the shell surface. Figures 18 and 19 show the behaviour of the Isler shell and the digitally form-found shell, respectively. Both show relatively low stress and deformation.

One limitation of the CAD environment is difficulty in calculating the long-term deformation. Isler addressed the importance of observing the long-term shell deformation after construction, to confirm its quality and to improve the next project. For the Sicli project, Isler monitored 10 points along the main axis for over 6 years (Fig. 20). The maximum deformation was about 1:1500 of the diagonal

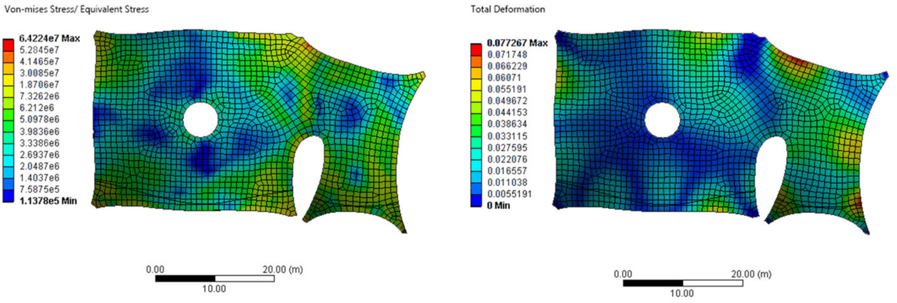


Fig. 18 Von Mises stresses (left) and deformation (right) of the Isler shell under self-weight and a uniform vertical load of 2000 Pa (Graphic: Chu-Chun Chuang)

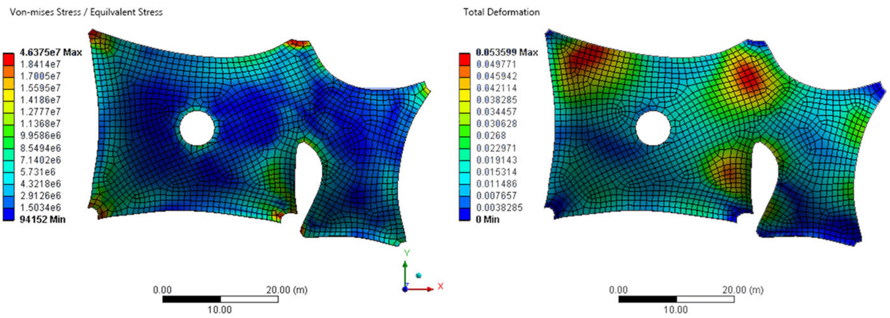


Fig. 19 Von Mises stresses (left) and deformation (right) of the digitally form-found shell under self-weight and a uniform vertical load of 2000 Pa (Graphic: Chu-Chun Chuang)

span, compared to the relatively small ratio of 1:50,000 for a swimming pool shell in Lugano (Isler 1980).

Two areas of the shell surface were considered to have shaping errors which resulted in larger deformation, although this stabilised within about 1 year of construction. These are point 61, which rose by about 55 mm and point 85, which sagged by around 30 mm. It should be noted that the FEA results also indicate a larger deformation near point 85.

Discussion

The theme of this special issue posed a number of questions, discussed here in the context of Isler's shells.

Are Efficient Structural Forms Inherently Beautiful? And, if so, Why?

Isler's shells, in particular those based on the hanging cloth reversed form-finding method, are recognised as some of the most beautiful and elegant reinforced concrete shells. They have been demonstrated to be efficient structural forms, supporting self-weight and applied loads with small deformations, whilst using the minimum of material. Their beauty comes from their close association with doubly-curved forms found in nature, which are generated by the laws of physics and strive to minimise the energy required in their formation. However, the graceful aspect of architectural shells is often compromised by functional requirements, such as the need for weather tightness, which necessitates the introduction of a façade. The effect on the shell aesthetic depends on how this is handled. If handled insensitively it may detract from one's appreciation of the "pure" shell form.

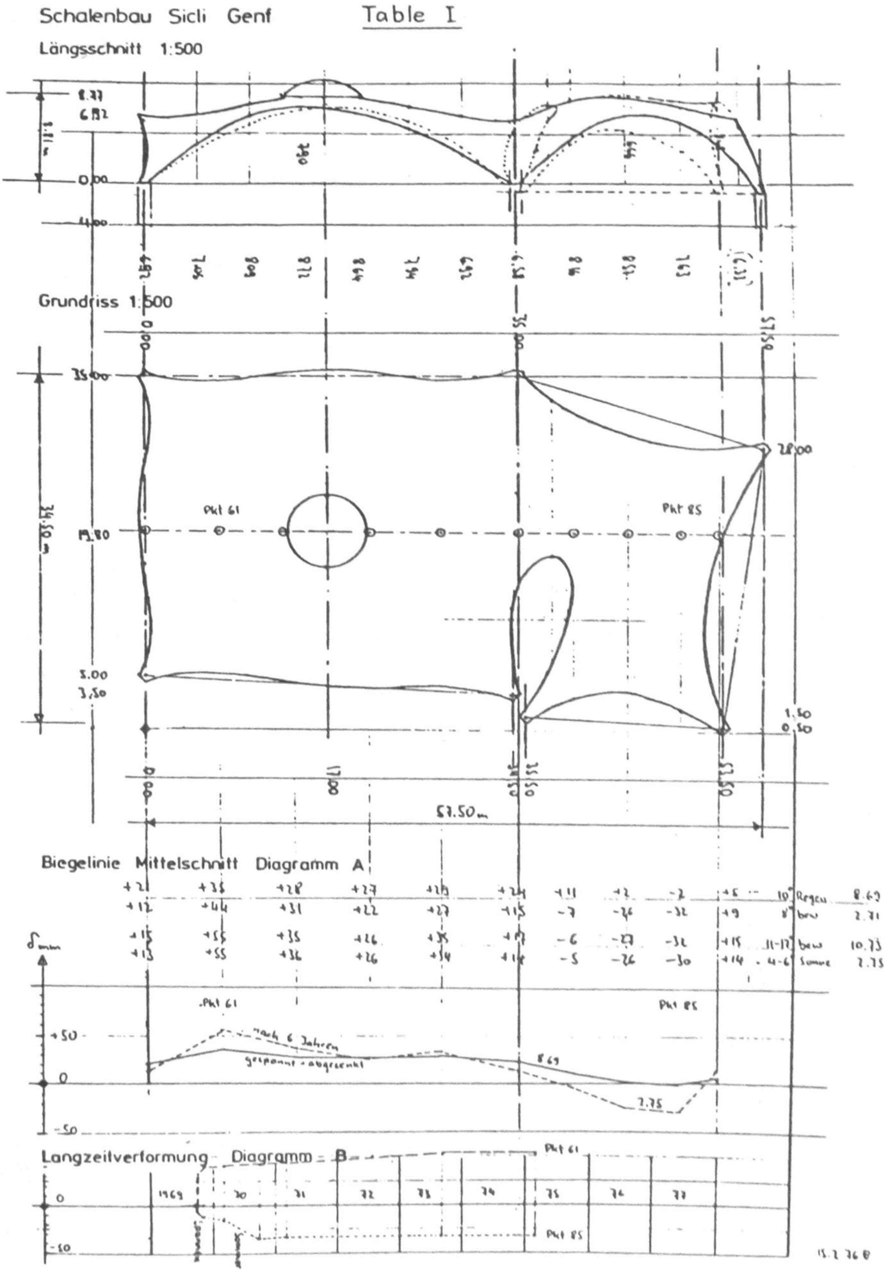


Fig. 20 Deformation on axis A, 6 years after the Sicli shell's construction (© gta archives/ETH Zurich (Holding Heinz Isler). Photo: Chu-Chun Chuang)

Is There a Mathematical Language Appropriate to Discuss and Evaluate Aesthetics?

It is difficult to imagine that there exists some general ideal proportion for double-curved thin shell architectural structures, equivalent to the golden ratio in rectilinear proportioned buildings, or the expanding growth spiral of the nautilus shell in nature, related to the Fibonacci series. Aesthetic values differ from each individual's point of view, although many objects appear more visually pleasing when they obey the laws of nature. In the case of thin shells, most examples of good design—displayed clearly in the case of Heinz Isler's shells—imply that the designer was following the same natural laws.

How Can We Generate Natural Forms in the Digital Age?

As Isler practised his design process the most time-consuming stages were to accurately measure the double-curved plaster cast formed on the hanging membrane, the construction of a physical surface model used to investigate the shell's structural performance and to check for buckling instability. In the digital age the creation of a hanging model is probably the most difficult part. Precise three-dimensional scanning of double-curved surfaces is now rapid and commonplace. The point cloud can be easily manipulated to generate a surface model, which can then be analysed using FEA.

Alternatively, the process can be fully digital. Particle spring simulation has provided opportunities for architectural designers to follow similar principles. However, there is a danger that designers will be seduced into limiting their form-finding solely to computer modelling. With digital tools, designers can create any kind of shape rapidly according to optimisation criteria. Perhaps this allows too much freedom. Basic factors in real time may be overlooked, such as the effect of scaling, construction feasibility etc., which can be exposed by a physical model. Fortunately, digital technologies can assist with digital fabrication available to create accurate and functional models.

Conclusion

Heinz Isler was a pioneer and master of free-form reinforced concrete shell design, achieved without modern digital computation. Indeed, he saw computer-aided design and analysis as a threat to his "natural" design method using a variety of physical models. The only computer in his office was used for word-processing and accounts.

Modern designers are unlikely to follow Isler's method precisely but can learn from his graceful and efficient shell forms:

- the importance of shaping—finding a structurally and materially efficient shell form
- the elements of shell construction that contribute to the overall architectural or artistic expression e.g. thinness of the edge
- the functional—e.g. relationship of the shell form to its architectural requirements and site context
- the constructional—efficient forming of complex curved surfaces.

With or without the aid of computers, designers are encouraged to explore and test their designs using different modelling approaches, including physical models. To produce a beautiful thin reinforced concrete shell requires inspiration and much patience.

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Chu-Chun Chuang is a qualified architect in Taiwan, who has studied and practiced in Asia. She was awarded a distinction master degree in architecture by University of Nottingham in 2014. Her passion for Heinz Isler and his thin shell forms were manifested in her master thesis. She combines her expertise in architecture with the knowledge of structure to convey research on historical aspects of free form shell design. As an architect, she has diverse experience on delivering healthcare projects and hospital designs around China and Taiwan to promote the integration of human and space. Her creativity has been demonstrated with manifold cultural awareness. In 2016 she moved to London and joined one of the British leading studio specialising on retail design. With her team she delivers numerous major shopping centres in Europe. Her responsibilities also involve BIM coordination and collaborating with various consultancy sectors to provide challenging retail schemes.