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Prefiguring digital methods, Frei Otto used media techniques and novel devices to translate between incalculable materiality and calculable information.

Material models, photography, and the threshold of calculation

Daniela Fabricius

Histories of the advent of architectural computation typically describe a moment of transition from physical models and drawings to codes, information and data, leading almost inevitably to the digital technologies of the present. However, the trajectory from material form and its calculated representation was not always so direct. The work of Frei Otto, and the Institute for Lightweight Structures (IL) that he founded in 1964 at the University of Stuttgart, is an example of how material experimentation, media techniques, and calculation came together in novel ways *[1]*. This history is distinguished by the fact that calculating machines played a minor role. In the 1960s and 1970s, researchers at the Institute for Lightweight Structures arrived at ways of making and calculating architectural form that was arguably proto-digital. But this began with entirely material processes that were not easily turned into numerical data, nor were they limited to the immaterial 'space' of the screen where every coordinate position – and thus every form – had to be numerically accounted for. Experiments, devices, tools, and modes of representation were developed to serve as means of translation between incalculable materiality and calculable information. Unlike early experiments with computation that happened largely within the black box of the computer, here the interaction between material objects and data took place in physical laboratories and workshop spaces.

1 Frei Otto with Eberhard Haug, pneumatic experiment with inflated intestines, 1973.

This negotiation between matter and its calculation was complicated by Otto's own ambivalence towards the emerging field of computer-aided design and his resistance to the mathematics of engineering. One could say that Otto was more interested in finding the *incalculable* than in any sort of *mathesis universalis* according to which everything could be potentially rendered into numerical information. Otto regarded calculation with suspicion; he considered the calculation of statics used by engineers to be 'coarse' and based on 'inexact assumptions'.[1] He writes that they 'will never have the same meaningfulness as the de facto testing of a real object by real forces'.[2] He continues:

> *until today there are buildings which cannot be grasped mathematically, meaning that they are – to use the exact term – 'incalculable'* [unberechenbar]. *In spite of this they can be built as constructions capable of bearing loads, which means they are reliable thanks to experience*.[3]

Otto argued for a method of experience and experimentation rather than finding form through 'theoretical planning with drawings and calculations which can today be supported by extensive use of computers'.[4]

The attempt to measure and calculate 'incalculable' structures was central to Otto's search for a zero degree of economy and lightness in architecture. Lightness is a complicated term in Otto's work, referring not only to the weight and efficiency of a structure, but also a moral and aesthetic principle in opposition to what he saw as the 'brutality' and heaviness of fascist and concrete architecture. Form-finding models and experiments provided Otto with a way to empirically test his theory of lightweight structures, transforming the economy of the 'laws of nature' into architectural form. In his 1954 book *Das Hängende Dach* Otto had already suggested a relationship between self-

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formation, economy, and lightness:

Hanging roofs cannot be designed. When every impure tone is avoided, one can help them unfold. They suggest a peculiar beauty that is perhaps closest to the plastic trace of the spider web: an appearance that one cannot draw or explain, that will unobtrusively elude us.[5]

An ideal structure is thus one that unfolds by itself, and in a way that is judged to be beautiful. The spider's web – a form and concept that preoccupied Otto throughout his career – is the ultimate example: it is a structure so minimal and light that it is almost beyond representation or analysis. Trying to capture and calculate such minimal forms, while at the same time insisting on their elusiveness, became a complicated ideal in Otto's practice. Otto was consistently less interested in these numerical results than he was in finding ways to maintain a threshold where matter could not conclusively be turned into numbers.

This threshold also betrays a conflicted relationship to architectural authorship. Like many of his contemporaries in the 1960s who were interested in automation, cybernetics, or intelligent machines, Otto was interested in self-forming structures, a preoccupation that indicates a fascination with the autopoietic. Though in Otto's case, this is tied to the behaviour of organic, or even inorganic, matter, not computation. He idealised self-formed structures as born from the intelligence (and what he assumed was the goodness) of nature, as opposed to the limited capacity, and potential brutality, of the human imagination. This interest in the elusive forms created by chemical, biological, or physical processes was directly related to his suspicion and criticism of fascist and modernist architectures and their effects on the German landscape.[6]

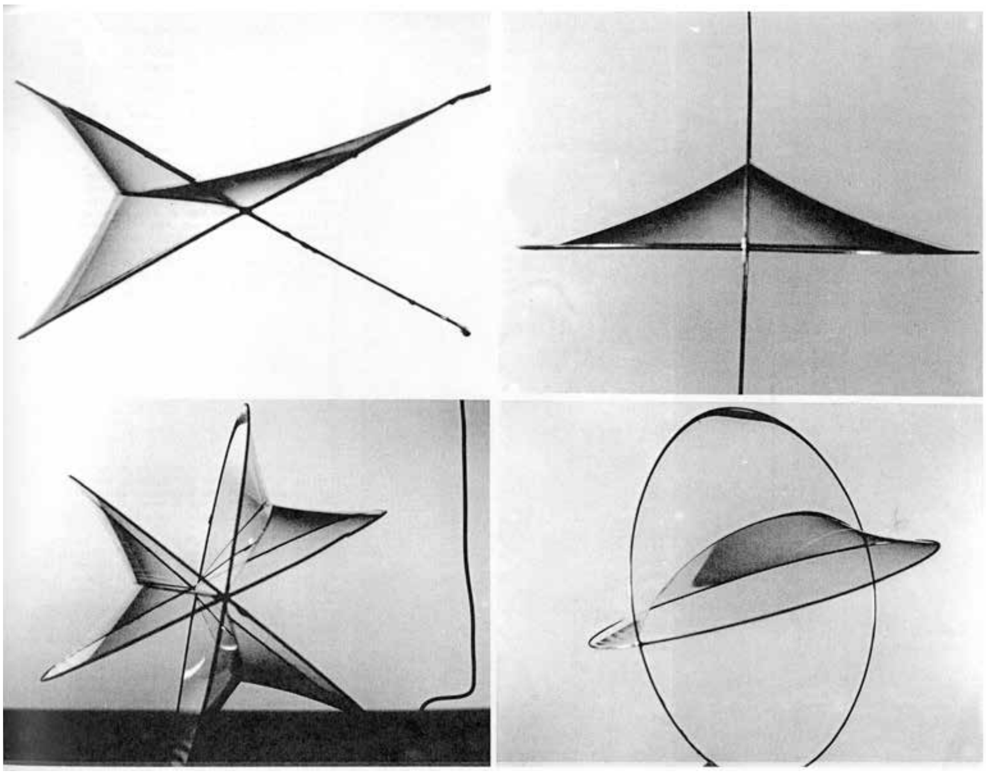
From model to photograph

Otto worked primarily with soap film models *[2]*. Soap film forms a structure of almost perfect optimisation. With a thickness of only a few molecules and a high and uniform tensile strength, it forms a closed structure, ideal for testing pneumatics, tensile roofs, and minimal path systems. For Otto, these forms seemed close to those found in nature, and were 'meeting the justified and growing demand that technology abandon its abstract, anorganic-mathematical conception, though not its scientific basis, in favour of a conception nearer to organic life'.[7]

But these self-generated forms are also highly ephemeral, usually lasting only seconds or minutes. Otto began experimenting with soap film at the small research institute that he founded in 1959 in a shed in his in-laws' back yard in Berlin.[8] An account by Ewald Bubner, a longtime collaborator of Otto, gives an impression of the provisional atmosphere in which these experiments began:

One day I arrived at the studio fairly early. Frei Otto was alone, blowing soap bubbles through a wire loop and chasing them back and forth through the studio to catch them and stick two or three bubbles together at a time. I asked whether he was all right – and was reassured when he answered that he was conducting a scientific experiment.[9]

Otto had an irreverent and conflicted relationship with the sciences, and frequently referred to himself as a '*Spinner*' (madman) and 'pseudo-scientist'.[10] His approach was symptomatic of the cultural paradigm of the 1950s and 1960s in West Germany where the critique of *Zweckrationalität,* or instrumental reason, was well-established in postwar architectural circles. Otto had absorbed his generation's criticism of the disastrous outcome of the rational-scientific



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2 Experiments with soap film in wire frames. Frei Otto 1960 / IL 1964. Published in *IL 18: Forming Bubbles* (1987).

3 Photos of interior of pig intestines taken by IL researcher, 1973.

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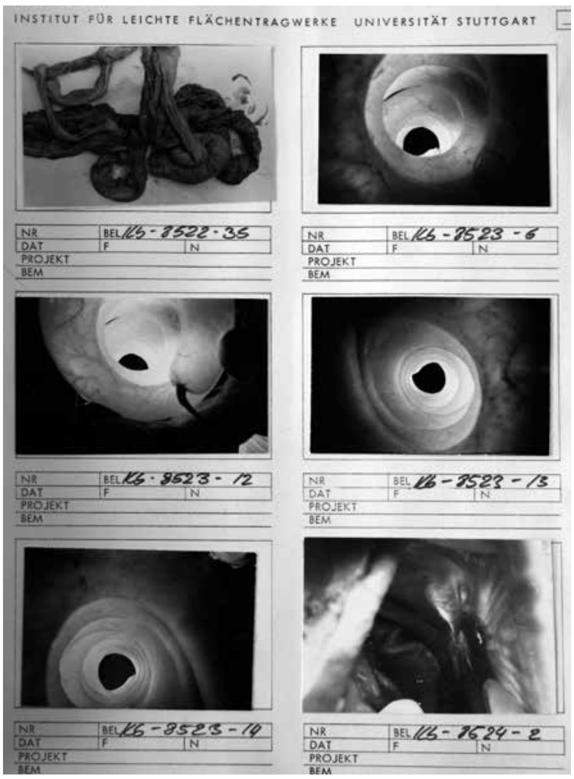
approach of postwar functionalism but was at the same time caught up in the *Verwissentschaftlichung* (scientisation) of culture in the 1960s and made full use of the new technologies and scientific instruments that were available to him at the Institute for Lightweight Structures.

Otto insisted on using physical models that emulated his organic conception of structures made 'without humans' but he also accepted the use of optical instruments as an extension of the senses to apprehend those models. He predicted that the dominance of analytic engineering would wane thanks to these 'newly developed, extremely sensitive instruments' that would usher in a renewed emphasis on observation and experience.[11] Otto believed that humans were inherently incapable of observing forms in an objective way.[12] Thus the emphasis shifts from the observer to the instruments and measuring tools, making the documentation, description, and classification of forms as important as the process of 'finding' or producing the forms themselves. Incalculable forms required a new method of observation: 'To define this range of variations of forms an attempt is made to introduce a method of observation which, on one hand, would be less "sharp" than the exclusive geometric models used until now, but on the other hand would be more comprehensive.'[13] These are forms in flux, defined by shifting parameters rather than exact equations.

Direct observation was thus understood as already mediated and enhanced through instruments that were borrowed from the sciences to document and measure material forms that were either too small and ephemeral, or too large and complex, to otherwise comprehend *[3]*. Optical instruments made it possible to study a range of organic and inorganic objects of different scales, which contributed to broadening Otto's conception (and classification) of possible architectural structures. This could include anything from atoms, crystals, blades of grass and seashells to planets and the Solar System.[14] These objects are (theoretically) calculable even if some are neither perceptible with the naked eye nor directly measurable. Photographic images of these objects thus played a primary role in the process of translation from material to calculation. Jürgen Hennicke, a long-time collaborator of Otto's, has confirmed that photography was 'the central medium' of the work at the IL.[15]



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Image, apparatus, number

Otto's early years of free experimentation with soap film had yielded a collection of attractive photographs and speculative ideas. Yet these comprised more the documentation and classification of forms than actual data. In order to measure the soap film models, they had to become more durable, which could be accomplished by controlling their chemistry and atmospheric conditions. They also had to be placed within a framework in which space was already constructed as measurable, where a total and precise coordination between object, camera, lighting, and background was possible. Here, I will argue that the devices developed for this increasingly came to take precedence over the models, becoming more sophisticated and eventually transforming into spatial models themselves.

The first soap-film device at the IL was constructed in 1965 to study minimal path systems *[4a,b]*. It consisted of a glass plate with a matrix board of pins suspended over a soap tank.[16] When dipped in the solution, the soap film would 'find' the most efficient path between the pins. The entire device was installed on a concrete slab in order to avoid vibration, and featured a glass cover to protect it from dust and evaporation, which apparently allowed for fragile soap membranes to be kept stable for up to three weeks.[17] An image shows a camera awkwardly mounted on a tripod to photograph the soap films from above. This camera was equipped with a water level to ensure that it is perfectly aligned with the horizontal plane of the glass plate. Where chance had in the past served as an aid to design, here it is a distraction that must be eliminated. A series of careful and repeatable protocols were carried out not so much for the creation of a model as for the creation of a perfect *image* of a model.

Images taken using the device show the formation of minimal nets between points, and were published along with simple calculations of the angles of the soap film as it slowly deforms and reaches equilibrium *[5]*. High-contrast, graphic photographs were used interchangeably with line drawings and calculations. Thus model, then image becomes data. The impression is that these photographs have the accuracy of a drawing.

Peter Galison identifies a shift in the history of scientific experimentation that is relevant here. He describes two methods of producing information in

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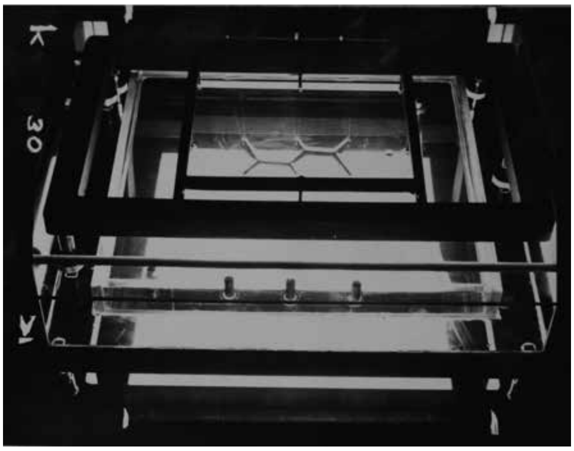

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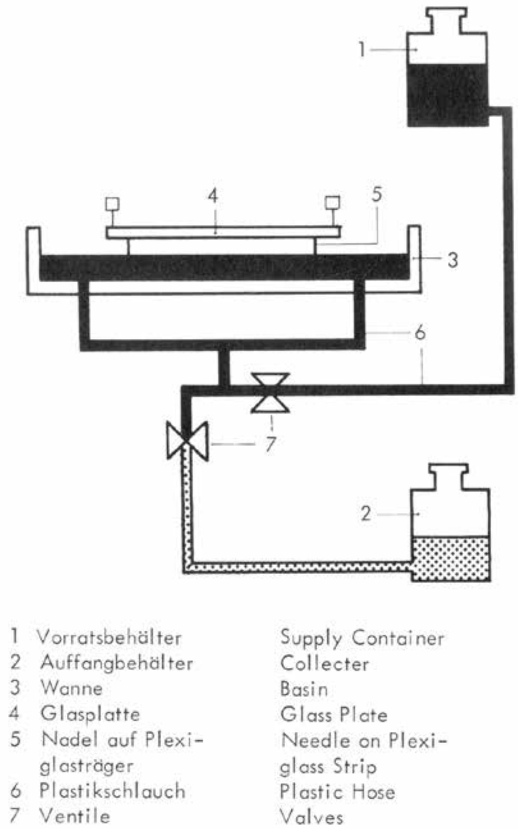

4b

4a,b Minimal path device, 1965.

modern science: photographic images that indexically record phenomena, and non-visual data or what he calls 'logic'.[18] According to Galison, image and logic converged during the 1980s with the rise of the electronic image. Frei Otto's experiments were conducted at the cusp of this transition and often tried to resolve these two types of information. For instance, this was done by translating photographs of soap film through analysis in drawings in order finally to arrive at mathematical calculation. In different ways, the photographs and models produced by Otto are both indexical *and* generative of data. However, with the increasing dependence on the photographic image in the research, this acts not only as an illustration but also as a measuring device: there are fewer calculations. According to the research team:

> *the use of the instrument enables analogue optimal procedures* [...] *without any complicated coding or calculation. This analogy permits simple measurement of sufficient exactness.*[19]

As Otto's team continued to develop a series of devices for soap-film structures, they became increasingly larger and more complex.[20] Instruments were borrowed from other sciences that could measure the diameter and tension of the soap film. More significantly, these apparatuses integrated ways of capturing the models photographically using special lights, plates and lenses. In the process, the goal was no longer to come up with a variety of forms – in fact, the form remained the same. The focus lay instead in improving the experimental setup and its method of documentation: the photograph. Thus, the making of the model was increasingly geared towards the camera.

In one setup, the soap film model is placed on an aluminium ring below a turntable that is able to rotate and thus shift the shape of the model by means of an attached string *[6]*. One should note the introduction of the kinetic element: the movement and manipulation of the model in space. From one side of the contraption a light source is projected onto the model. The light is located at the considerable distance of 15 m in order to approximate parallel light waves and reduce distortion. A sheet of photo paper is inserted behind the model. Once exposed to light, it creates a photogram. Photos were taken with rotations of the model in increments of ten degrees, allowing for a 'scan' of the form. This can be read as a crude version of today's 3D scanning, measuring an object in space in order to replicate it.

Subsequent iterations further eliminated imprecision to allow for more accurate measuring. In one, the photo paper is replaced by a frosted plate etched with a millimetre grid. The image of the model was projected onto this screen and photographed with a large-format camera *[7a,b]*. The entire device, which appears to have been several metres long, was mounted on an optical bench with four convergent lenses to create parallel light projections. By now, it is clear that another shift had taken place: the apparatus for creating and documenting the model has become larger and far more difficult to produce than the model itself. In a further variation, the structure suspending the model could not only be rotated but also inverted to study the possible effects of gravity. The resulting photographs became the basis for plotted contour lines that could produce a 'precise' drawing, and even a plaster model, again calling to mind 3D scanning and plotting technologies. Here, as in the early experiments with minimal networks there is a process of moving from model to photograph to drawing, or a transition from image to data.

The final and most elaborate apparatus, which is still in use at the IL today, was first developed in 1973.

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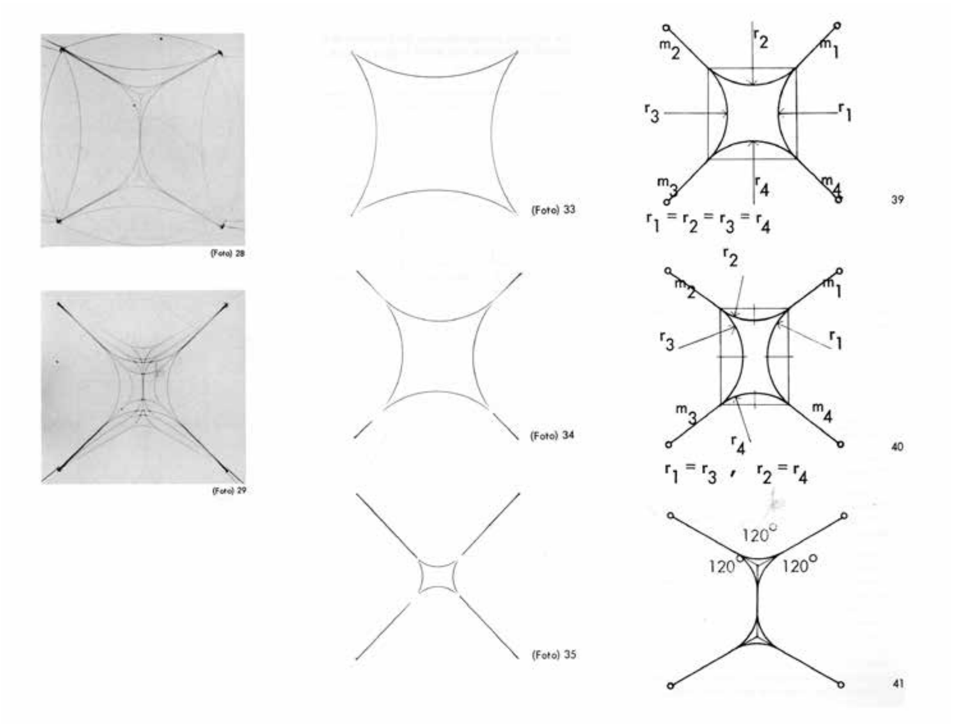

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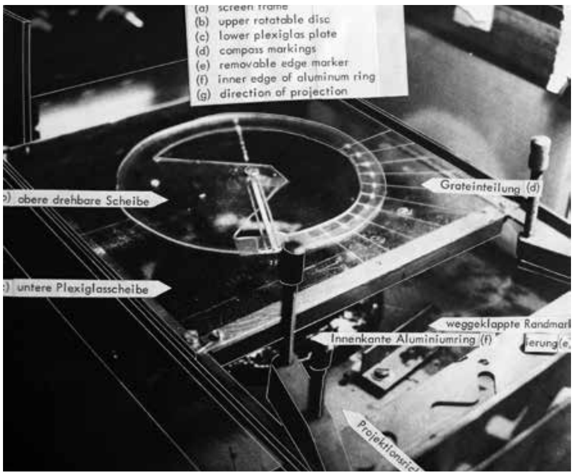
5 Photographs, drawings and calculations of minimal nets between four points reaching equilibrium, c. 1965. Published in *IL 1: Minimal Nets* (1969).

6 Soap film model measurement setup with turntable. Walter Reinhardt and Stefan Waldraff, *Bestimmung der Geometrie eines Minimalflächen-Seifenfilms zwischen Kreisring und schlaufenförmiger innerer Unterstützung*. IL student research project, 1967-8.



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The comical-looking machine is a large assemblage (about 7 feet tall and 9 feet deep) of acrylic basins, rubber and plastic tubes, dials, steel frame supports, a spindle, light box, and camera *[8]*. Aesthetically, it calls to mind the air, apparatus and machine-based fantasies of the avant-garde of the 1960s. In that sense, it plays off the utopian idea of a device that harnesses technology to create instant, adaptable, autonomous architecture. It is at the same time not unlike the self-contained world of the computer, in which model creation, measurement, calculation, and output are enclosed in one machine.

In this machine, the model is housed in an air-conditioned chamber surrounded by glass and acrylic. A camera is mounted on an adjustable support in front of the chamber. The support for the soap film model can be fully manipulated using a spindle and fork, which not only adjusts the height but also allows it to be rotated 360 degrees and swivelled 180 degrees. This recalls the disorienting space of the digital model in which it is no longer the viewer who moves around the model but the model that is manipulated in space according to its axes.

One can make several observations in looking at the evolution of these devices. The onus of representation is no longer placed on the model but on the apparatus that documents and measures it. The object is overwhelmed, and nearly disappears, in the device that measures it and converts it to data. Form-making and 'scanning' are integrated into one machine. The question is no longer that of analogue representation but the extraction of numerical data that can be applied across scales.

As these devices became more sophisticated it was clear that the image had gained prominence, perhaps even over spatial form. As a result, the experiential and phenomenological aspects of image-making and observation were also emphasised. For instance, a 1973 IL publication included a pair of groovy 3D glasses for the reader to view a series of anaglyphic images printed in red and green at the centre of the book *[9]*.[21] Similarly, the reason for using this technology at the IL was surprisingly tied not only to perception but also to precision: the researchers argue that the 3D images are more 'realistic' spatial representations without distortions, unlike 2D drawings which were viewed as inadequate to describe new forms that do not follow 'simple geometric laws'.[22]

While the measuring photographs had attempted to capture an object in order to flatten it into data, there is an effort here to virtually maintain the object in three dimensions. This was not only done using cameras, but also later with measurements taken from models that were processed through a computer and plotted in red and green ink. In this reconstitution of the object, even the physiology of the human eye was calculated. Research was done on the distance between a human's eyes, the ability of the brain to perceive depth and the desired focal distance and

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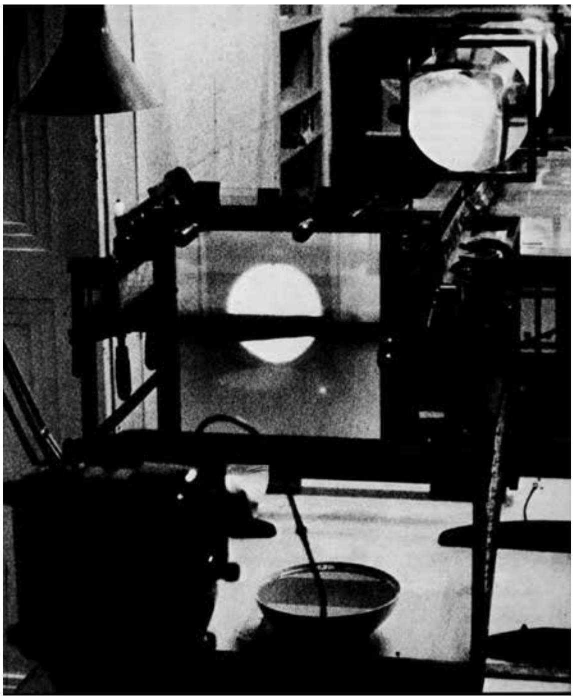
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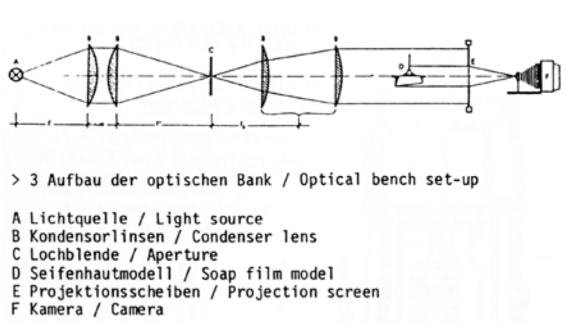

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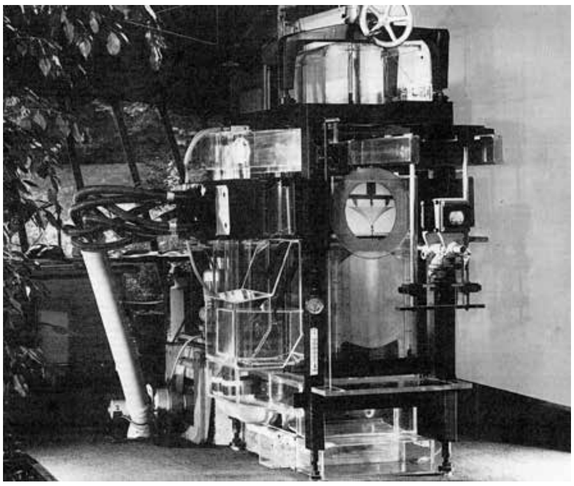
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7a,b Soap film model measurement setup with optical bench. Walter Reinhardt and Stefan Waldraff, *Bestimmung der Geometrie eines Minimalflächen-Seifenfilms zwischen Kreisring und schlaufenförmiger innerer Unterstützung*. IL student research project, 1967-8.

8 Seifenhautmaschine (Soap film machine). IL, c. 1973.

angle so as not to produce blind spots. These were all mathematically calculated in order to produce an ideal architectural representation in the mind.[23]

While Otto had placed much emphasis on the importance of image technologies as an expansion of human vision and the physical realm, those technologies were also used here to alter, enhance, and direct human vision – in other words, to insert themselves in the process of perception itself. The 'imperfect' eye, which Otto thought to be not entirely capable of objectivity, was helped along so that the brain could produce a more realistic image. In a significant step towards simulation (and computer modelling), the traditional architectural drawing and its outdated technology of perspective were seen as no longer sufficient. These images suggested something closer to a simulated image and one that, unlike the fragile models, could be stored, reproduced, and transferred in the form of media.

The incalculable *pneu*

Not all form-finding at the IL took place within the carefully controlled space of the measuring apparatus. In the laboratory, photographs of models became increasingly precise, serving more as the basis for measurement than the discovery of new forms. In 'the field', however, the quest to collect and document new and incalculable forms led to a very different use of photography. At the intersection between forms found in experiments and those found in nature lay Otto's theory of the *pneu*.

The pneu represented what was perhaps the furthest limit of the immeasurable and incalculable in Otto's work. The pneu refers to pneumatic structures, but only tangentially. Otto viewed the *pneuma* as a universal concept of enclosure found in all nature, especially in the human body. Otto believed that the pneu was tied to the origins of life - '*Am Anfang war der Pneu*' ('in the beginning was the pneu') - and it stood as 'the essential basis of the world of forms of living nature'.[24] Otto's interest in the pneu was not related to its function or morphology but rather simply to its structural properties. Pneus represented not only some of the lightest forms in nature, but were also considered the most optimised. The pneu no longer referred only to pneumatically-strained membrane structures but to all membrane envelopes or even forms (like shells or the inside of bones) that result from the hardening of once-moist membranes. With the pneu, Otto claimed to be able to account for every form in nature.

Whereas Otto elsewhere used numbers and data to create a universal system of forms the main vehicle for the pneu was photography. Modern architects have generally understood the sciences only through appropriated images. These, according to Antoine Picon, are borrowed by architects not for their content (for which they often did not have the expertise) but for their 'imaginary social signification'.[25] Otto takes this imaginary a step further by not only appropriating scientific images but by creating them. Photography plays a double role as a tool of both precision and architectural projection.

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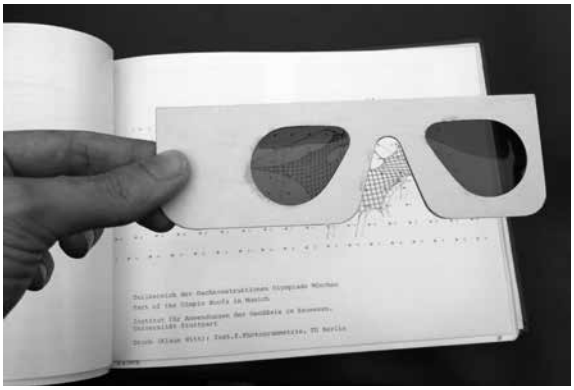

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9 *IL 6: Biology and Building* (1973) with anaglyph images and 3D glasses.

Photographs were gathered by the IL team members from science publications. They also were taken during visits to zoos, slaughterhouses, and markets. Because the pneu in nature needed no model, so to speak, the photograph became the vehicle through which the natural and the architectural could be placed within the same conceptual system. The great amount of material gathered seemed to have no limits, and as a result, the definition of pneu seemed just as boundless. Images collected under the title of 'pneu' were extensive and heterogeneous, and included unusual and taboo subjects. There were 'found' structures like sails, rubber tubes, upholstery cushions and fishing nets, but also pig intestines, microscopic images of pollen, corn cobs, frog spawn, vegetables, icicles, cells, car tires, amoebas, a human egg 'a few instances before fertilisation', dividing salamander eggs, clouds, algae colonies, seahorse skin, human skin, a cow's heart, a Venus flytrap, multiple exposures of a human penis becoming erect, a section through the finger of a human foetus, a pig's bladder, 'the testicles of a 20-year-old man', an apple next to an image of a girl's navel, a slug, a human brain and skull, and a naked pregnant woman with two children *[10]*.[26] The theory of a universal membrane was so expansive that it was able to contain images of seemingly unrelated objects.

One of the things that made the pneu a difficult object of study – and what links it to the soap film experiments – is that it is attributed to living, mutable things and is thus difficult to capture. Otto was interested in these 'highly unstable' and transient qualities of life (or the utterly ephemeral) and their unique structural properties. Unlike the finicky precision of the soap film models, the study of the pneu was looser and less precise, more focused on the observation and classification of structures than measuring. According to Otto's theory of aesthesis, which he defined as 'the ability to perceive the aesthetic', optimal lightweight form could be innately perceived. Otto viewed the pneu as a special subject for which man 'does not yet have the necessary scientific objectivity'.[27] Photography thus became the preferred method of reframing and collecting forms that the mind resists. For Otto, conservative moral responses to the cultural taboos suggested by these forms were analogous to the resistance to new forms and geometries in architecture. Thus, the incalculable is also that which is taboo, and the *Hemmungen* (inhibitions) he describes limit both architecture and science.

As the IL researchers moved further into the terrain of science, especially biology, they allowed themselves greater imprecision. Their contradictory methodology asks for precise measurement on the one hand, but also room for subjective experience in order to embrace 'unknown forms'. They argue that in order to avoid a recourse to Euclidian geometry used to describe 'known' objects, observation is needed that would defamiliarise everyday objects (spider's webs, human bodies, etc.) and allow for the recognition of unknown forms. These nevertheless ultimately need to be captured as data:

> *A highly developed technique exists for measuring forms by scanning and storing the data. Simple forms require hundreds of datum to permit their adequate description. Complex forms often require millions of datum so that the form can be stored with certainty and recognized reliably by many people*.[28]

As the complexity of a form increases, so too does the amount of information needed to capture and reproduce it, suggesting an eventual return to calculation. When it came to the construction of large, sophisticated projects, Otto's institute turned to new instruments that could process this increased quantity of data; new tools were needed that would 'permit the comprehension of thousands of data "at a glance"'.[29]

From incalculability to computation

While the pneu represented the not-yet-attained and perhaps immeasurable ideal of a universal, optimised structure, Otto's built projects demanded precise measurement and calculation. Measurement models, designed to produce data objectively, lay at the other end of the spectrum of calculability. These models yielded numerical information about stresses that were difficult to comprehend visually and still impossible to calculate mathematically. Forms were arrived at through inductive methods, then tested in models that generated information, which was fed back into the structure. Paradoxically, once an optimal form was found, whether by soap film or other self-forming methods, it lost its mutability due to the complex and inflexible nature of minimal surfaces. This was especially the case for structures with inconsistent loads made of more rigid materials like the cable net roofs for the 1972 Olympic Stadium in Munich. While the overall form is largely stable in these models, change instead occurs on the micro-level, captured by tiny gauges and stereoscopic cameras *[11]*. The structure is a system that generates new data with every minute change, a predecessor to today's parametric design.

Otto had constructed measurement models and form-measuring devices as early as the 1950s but needed more sophisticated methods when he was commissioned to work on large cable net projects,

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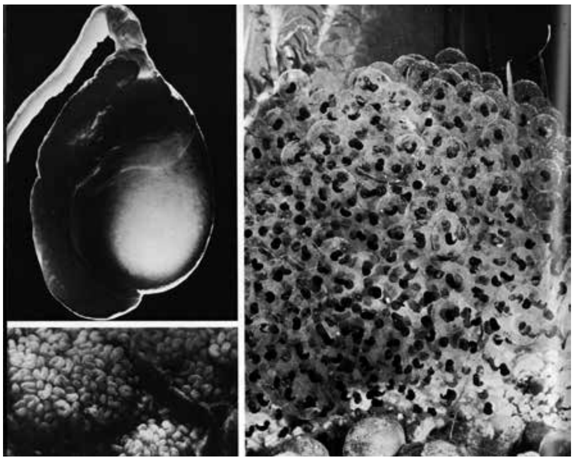
beginning with his design for the German pavilion at the 1967 Montreal Expo. Unlike the nearly immaterial liquid surface of the soap film, cables and connections on a matrix allowed for the isolation of individual points. These fixed points made it possible to position these forms within the coordinates of Cartesian space, and eventually allowed for Otto's work to be digitally modelled.[30]

These types of measurement models sacrificed resemblance to the building in favour of a 'picture' of the building in numbers. In order for a structural model to be measured, it typically has to be 'disfigured' with sensors and markings, like 'a sick body, to the point of rendering it unrecognizable'.[31] Measuring instruments attached to a model, however precise, also modify and distort the results.[32] The model becomes hyper-rationalised as it requires further technological intervention in order for it to correct its own (mis)behaviour.

The metal wire models that were built beginning in the mid-1960s at the IL indeed resembled a technologically-sustained body *[12]*. They were loaded with weights and springs to create strain, and outfitted with stereophotographic cameras and gauges that could register movement to one tenth of a millimetre. As in the soap film experiments, a physical model was combined with a method for precisely documenting it both photographically and numerically. These models were quite large and could be adjusted according to the feedback given by the measurements, by changing weights or wire tension. The flexibility (or what would today be called parametric logic) of the models would eventually be built into the construction of the actual buildings: the tension of individual connections in a cable-net structure could be adjusted via clamps, giving a clear material expression of its internal forces.

For the 1967 Montreal pavilion, a cable-net structure with irregular peaks covering 10,000 m^2 was designed. This was the largest cable-net structure to be built at the time. Linear calculations of a structure of this type were impossible for 'an interchange system that was highly statistically indeterminate internally'.[33] The model was thus key to this method of 'calculation'. The use of pre-tensioned wires in the model simulated the stresses of the built structure but at a smaller scale. This had the effect of minimising the representational distance between building and model. When the pavilion was erected in Montreal, the system could be adjusted by manually adding or releasing tension via clamps, thus performing optimisation on the building itself.

During the time of the Montreal project, mathematics also took on increasing importance. With public funds available from the German government and private funds from the Stromeyer tent company, the engineers with whom Otto worked began to develop mathematical formulas for tent structures. Otto initially embraced these new methods, particularly the geodesic experiments under Klaus Linkwitz at the TU Stuttgart, and later those of John Argyris, who developed computer-



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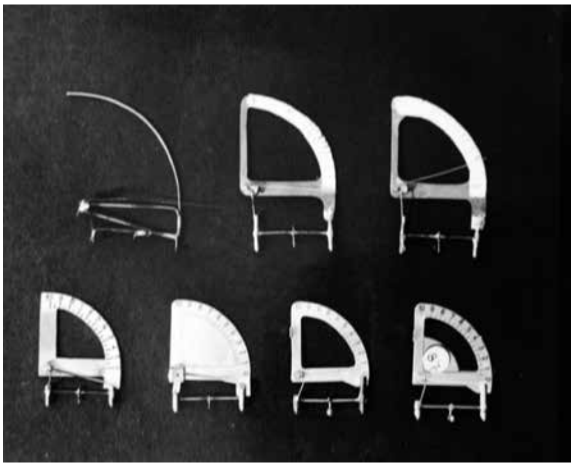

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based calculations. In 1976 Otto stated that a barrier was broken when 'the computer became a help' and 'there were persons like the members of the Argyris team, who could play it like virtuosos'.[34]

However, the transition from modelling the incalculable to calculating models with the computer did not happen so smoothly. The turning point was during the design and construction of the Olympic stadium roofs, in which the IL played a significant part. The 1972 Olympics project was about ten times larger than Montreal and it was built to be permanent, requiring a much greater investment. Otto's involvement was especially intense in the spring of 1968 at which point 'there existed no methods yet for mathematical analysis of cable nets', and 'experimental methods of model making had to be employed for the determination of the final form and for the investigation of the carrying behaviour'.[35]

Working with teams led by Günther Behnisch and Fritz Leonhardt, a design model made in tulle fabric was created and accurately measured.[36] Based on the tulle model, several very large measurement models (the largest was 1.9 x 4 metres) were constructed. A net of wires was soldered together and hung into the model, where it was subjected to various methods of producing and adjusting tension using springs and screws. What made these models so impressive is not only their scale but also their machine-like precision. This was a form of physical computing. Nothing in the construction of the models was arbitrary, and all

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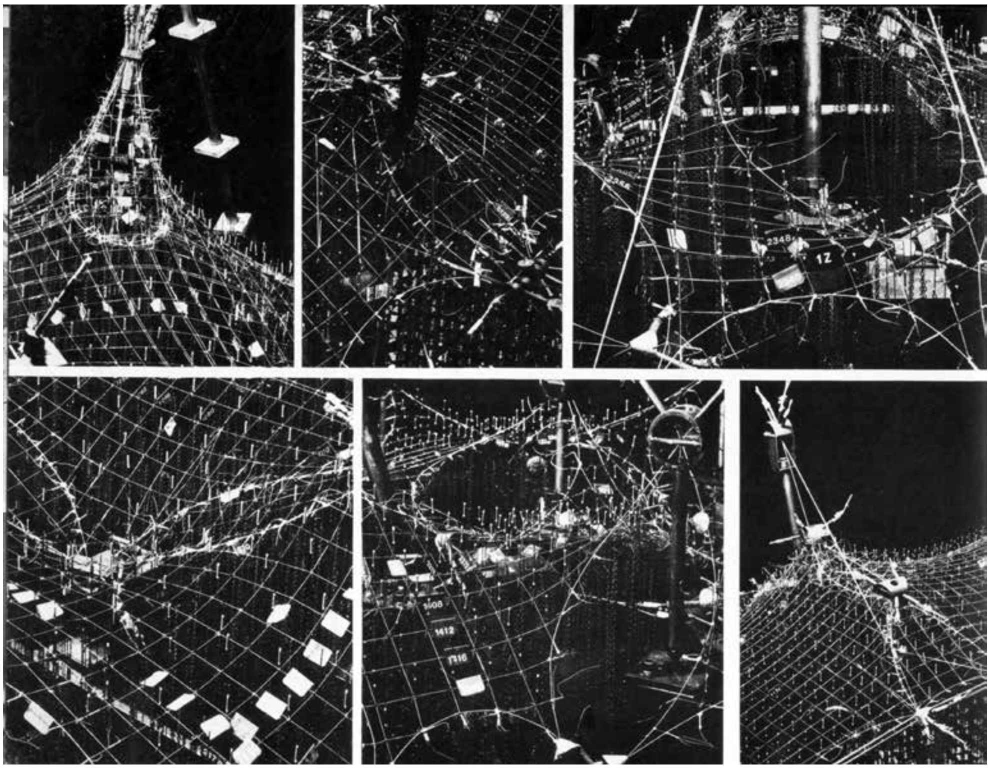
10 'Pneus within pneus': 'Testicles of a 20-year-old man' – 'Inside of testicles with canaliculi' – 'Frog spawn'. Published in *IL 9: Pneus in Nature and Technics* (1976).

11 Gauges for use in measuring models, 1967.

12 Details of Olympic Stadium measurement model, c. 1968.



12

of the performance variables were scaled down. For instance, spring wire, dimensioned and cut to scale, was pre-stressed proportionally according to the actual cables.

The actual measurement of the model took place following several criteria. The overall geometry and position of the coordinates in the system were determined by the use of a measuring table. This large structure, a kind of virtual Cartesian space, was able to trace and measure the geometry of a complex model through the use of a plummet. The data obtained could be read and stored through a computer in the form of punch cards or plain text. These values were saved or transferred to a drawing that was positioned above the model. This method, like the soap film model drawings, created an indexical 'scan' of the model.

A greater level of information was obtained by the use of photography combined with special measurement devices. Measurement here was less a question of dimension than performance. Individual wires were hung with number tags so that they could be identified in photographs. Every coordinate was a unique instant in which intersecting wires must be in equilibrium. The model was pulled by means of chains and weights simulating different loads and devices were developed that could read minute changes. Thus, while in the case of the soap film models increasingly larger devices were produced that eventually engulfed the models, here the development was towards ever smaller tools. These were, in effect, sensors embedded within the model.

While the soap film models had been photographed in their entirety so as to capture a total image of the form, here the model was photographed in close-up sections. The enormous quantity of data contained in the model, not yet translated into digital information, could only be documented with the camera, and in parts. Not only single instances, but also multiple layers of information were recorded through time-lapse photographs that showed the model change under strain. These jittery photographs documented a blurred landscape of grids, dials, and numbers. With these images, we return to the early modernist desire to capture form in motion, and change through time, using photography. But however similar the effect, the objective was different: to control movement rather than release its potential energies; to predict the future of architecture mathematically rather than imagine it. Using Galison's analogy, these images combined once again the indexical image with numerical data.

The calculation of the Olympic stadium roof structures took place between 1968 and 1972 with the most intense activity at the IL taking place over two years. During this time, an extraordinary number of developmental steps were taken with multiple experiments, versions, and adjustments as the optimal form was approached. This involved an iterative process of fine-tuning and self-correction through a series of protocols that were no longer just linear but also repetitive. One of the most difficult tasks was the manual tensioning and re-tensioning of thousands of wires until equilibrium had been reached at every point in the structure.

In contrast to this careful adjustment over time, a temporality of immediacy is evident in what was called the 'multimedia test'.[37] The great sensitivity of the Olympic stadium model made it vulnerable to imprecision if too many subsequent tests were run. Thus, researchers devised a way to take an informational snapshot of the model. With this test,

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the attempt to converge all of the data that could be obtained from a model was brought to a new level. The photograph shows what seems more a test site or performance stage than a model [13]. Hundreds of instruments were attached to the wire mesh model and the weights that hung from it were all suspended at once as a pneumatically-controlled floor below deflates. Surrounding it, in a manner resembling a television studio, was a battery of cameras, from which bundles of wires emerged.[38] This setup can be seen as a composite object made up of both the model itself and the devices that measure, adjust, and document it. The two became indistinguishable, together forming an architecture as much about form as about information. Here the solitary scientific observer looking through a lens (whether that of a camera or microscope) was displaced; they instead became a reader and analyser of data after the event. Information was viewed not with one eye but many cameras, multiplying the observation experience so that the object could be seen from all sides at once. With this assemblage of architecture and devices, the panoptic quest to view 'thousands of data at a glance' was achieved.

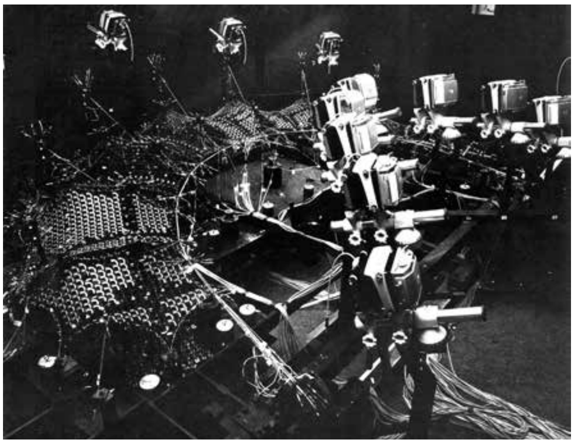
The models thus served as a means of visualising architecture on the one hand but also generating information on the other. With the hypothetical predictions and simulations, there never was a 'final' model. This brought it closer to the use of systems theory, calculation and mathematics to model, simulate, and predict a variety of behaviours.

Risk, precision, and calculation

But how accurate was this data really, and how detailed? An enormous amount of information was produced simply by the intricacy of the model and the detailed manual adjustments provided by the 'cheap labour' of the IL students. As computer models were increasingly able to calculate complex structures, it became clear that the analogue technologies used in the models were in some ways primitive. The measurement models generated patterns for cable lengths that were directly translated to the manufacturing and construction process. But the patterns were simply not accurate enough. As Linkwitz put it: 'A cutting pattern determined in this direct and rather simple way would result in intolerable risks.'[39] While the pavilion in Montreal had been determined using these methods, the very definition of precision seemed to have changed in the interim:

> *From geodesy and experimental natural sciences we know* […] *that 'exact' models and measurements in the very sense of the word 'exact' may be imagined mentally, but do not exist in physical reality. Therefore the measured spatial coordinates describe the theoretical exact configuration of the net only with a certain blur* […].[40]

Thus, at the same time that the measuring models were constructed to replace calculation, they were replaced by a newer form of calculation. The teams of both John Argyris at the Institute for Statics and Dynamics of Aerospace Structures, and Klaus Linkwitz at the Institute for Geodesy separately



13 'Multimedia' test of simultaneous measurements of the Olympics roofs model using 6x6 cameras, miniature cameras, and gauges. IL, c. 1968.

worked on methods of calculating the structure using computers.[41] Linkwitz began work on a 'theoretically correct model' in which equilibrium was simultaneously calculated for all points in the net so that loads could be equally distributed. These calculations, some of which required equations with up to 8,000 unknowns, were processed on a CDC 6600 supercomputer originally used for nuclear physics research.

Meanwhile, the engineers Fritz Leonhardt and Hans-Peter Andrä began collaborating with Argyris. The problem faced by the engineers of the Olympic stadium roofs concerned not only the calculation and measurability of the form, but the behaviour of each moment in the structure (which could number into the thousands). With the adjustment of the tension, or the position of a single cable in a net system, every other point is influenced. Thus, there was no 'typical' moment in the structure. The problem of this great amount of information had not yet been faced in the continuous surfaces of membrane structures.[42] Using data obtained from the IL models, Argyris's team wrote several programs for determining a state of equilibrium between over 10,000 points in the cable net structure and the fixed anchors at the site. They also ran equations for snow and wind loads and used plotter outputs to iteratively adjust the design. During the course of developing this method, the speed of calculation increased from three hours to twenty minutes.[43]

In the end, the three teams brought different parts of the project to completion using different methods. The transition from relying on Otto's physical models to calculating the information on computers took place very quickly. By this time, it was also clear that Otto had distanced himself from the process. As Jörg Schlaich wrote:

> *Frei Otto could be* [the] *team leader. But actually he was and still is against the computer applications. Of course he has developed all these methods himself. He*

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> *is a man who is not deep in the mathematical field; of course for him all computer calculations are suspect. He wants a model and sees then what happens.*[44]

Indeed, Otto had created a form of architecture so dense with information and potential risk that it could probably have only been executed using the computers. The complexity of the structure and its extremely tight tolerances created a system in which change could only be 'processed' and managed by simultaneously solving thousands of nonlinear equations. The use of computation changed the architecture itself, moving it further away from Otto's ideal of lightness.

The role of Otto's models within the history of digital architecture is of great significance, but to subsume it within this technological history would miss the opportunity to speculate on the potentials of the assemblages of matter, form, information, and image that were created during these experiments. Sanjay G. Reddy writes that 'a risk-based conception of the world [...] made of it a fabric that was essentially knowable'.[45] Science promised to make uncertainty knowable through calculation and probability, such that the calculability of risk gave authority and legitimacy to those institutions (including think tanks like the IL) that could claim to produce a 'calculable mapping of the future world.'[46] With his concept of the pneu, Otto attempted to open up the possibility of the incalculable and unknowable. But with the criteria of optimisation determining the selection of these forms, they were already integrated into a system of measurement. Could a space for what Reddy calls 'radical uncertainty' be created at the IL? As the case of the Olympic stadium project shows, uncertainty was intolerable and a clear calculation and management of the complexity of the risks eventually had to be carried out by other means, namely by pure calculation.

Notes

1. Universität Stuttgart, Institut für Leichte Flächentragwerke, ed., *IL 24: Form Force Mass 4 – The Lightweight Principle*, Information of the Institute for Lightweight Structures (Stuttgart: Karl Krämer, 1998), pp. 33–34.
2. Ibid.
3. Ibid., p.34.
4. Universität Stuttgart, Institut für Leichte Flächentragwerke, ed., *IL 21: Form, Force, Mass 1 – Basics*, Information of the Institute for Lightweight Structures (Stuttgart: Karl Krämer, 1979), p. 63.
5. Frei Otto, *Das hängende Dach: Gestalt und Struktur* (Berlin: Bauwelt, 1954), p. 158. Translation by author. This was a publication of Otto's dissertation, completed in 1953.
6. He would later describe this as 'Heimatzerstörung durch Häuser' ('homeland destruction through houses'). Frei Otto, 'Mit Leichtigkeit gegen Brutalität', in *Schriften und Reden 1953–1983*, ed. by Berthold Burkhardt (Braunschweig: Vieweg, 1984), pp. 128–32.
7. Frei Otto, Rudolf Trostel, Friedrich Karl Schleyer, *Tensile Structures: Design, Structure, and Calculation of Buildings of Cables, Nets, and Membranes*, 2 vols (Cambridge, MA: MIT Press, 1967), p. 10. This is a translation of *Zugbeanspruchte Konstruktionen*.
8. Otto named this institute the Institute for Development of Lightweight Construction. In *Zugbeanspruchte Konstruktionen*, 1962, Otto makes reference to only one historical source for his soap-film experiments: *Soap Bubbles, Their Colours and the Forces which Mould Them*, by C. V. Boys, first published in 1890. Boys gives specific references and instructions for his experiments, many of which Otto repeated.
9. Ewald Bubner, 'Institute for Development of Lightweight Construction and Atelier Warmbronn', in *Frei Otto: Complete Works*, ed. by Winfried Nerdinger (Basel: Birkhäuser, 2005), p. 83.
10. Frei Otto, 'Ein Interbau und ein Spinnerzentrum', in *Schriften und Reden 1953–1983*, ed. by Burkhardt, pp. 89–97. This article was originally published in *Allgemeine Bauzeitung*, 36 (1970), 4.
11. Institut für Leichte Flächentragwerke, *IL 21*, p. 63.
12. According to Otto this is due to a number of factors including environment and psychology. See Institut für Leichte Flächentragwerke, *IL 21: Form, Force, Mass 1 – Basics*; Universität Stuttgart, Institut für Leichte Flächentragwerke, *IL 22: Form, Force, Mass 2 – Form*, Information of the Institute for Lightweight Structures (Stuttgart, Karl Krämer, 1987). Otto wrote: 'a highly objective description of a form can automatically stimulate a subjective observation by the recipient. Thus even extreme objectivity in description does not ensure an objective observation.' Institut für Leichte Flächentragwerke, *IL 21*, p. 16.
13. Ibid., p. 17.
14. Ibid., p. 16. Otto also mentions Charles and Ray Eames' 1968/1977 film *Powers of Ten* in relationship to this concept of scaling.
15. Jürgen Hennicke (Instructor, IL, now called ILEK), in discussion with the author, February 2013.
16. References now also include the work of nineteenth-century Belgian physicist Joseph Plateau and the German-American mathematician Richard Courant, who in 1940 published his accounts of soap film experiments, many of which were repeated at the IL. It is a diagram of one of Courant's experiments that leads to this first apparatus for soap film structures.
17. Universität Stuttgart, Institut für Leichte Flächentragwerke, ed., *IL 1: Minimal Nets*, Information of the Institute for Lightweight Structures (Stuttgart: Karl Krämer, 1969).
18. Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago: University of Chicago Press, 1997), pp. 19–21.
19. Institut für Leichte Flächentragwerke, ed., *IL 1*, p. 46.
20. Between 1967 and 1968 two students, Walter Reinhardt and Stefan Waldraff, were dedicated to developing a soap film device for three-dimensional forms. Walter Reinhardt and Stefan Waldraff, *Bestimmung der Geometrie eines Minimalflächen-Seifenfilms zwischen Kreisring und Schlaufenförmiger innerer Unterstützung*, IL student research project, 1967–8, IL Archive.
21. Universität Stuttgart, Institut für Leichte Flächentragwerke, ed., *IL 6: Biology and Building 3*, Information of the Institute for Lightweight Structures (Stuttgart: Karl Krämer, 1973). Here one can look to the influence of Otto's long-time collaborator, Johann

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Gerhard Helmcke, whose 1953 atlas of microscopic photos of diatoms had also included a pair of stereoscopic glasses, with the explanation that 'only in this way is a spatially correct (*raumrichtig*) impression of the framework of the structural elements possible'. J. G. Helmcke and W. Krieger, *Diatomeenschalen im elektronenmikroskopischen Bild, Volume I*, 2nd edn (Weinheim: J. Cramer, 1962), p. 3, my translation.
22. Bertold Burckhardt, 'Zum Problem Darstellung von Formen Anaglyphendrucke', in Institut für Leichte Flächentragwerke, *IL 6*.
23. D. Schwenkel, 'Three-Dimensional Perspective Representation of Structures Using Automatically Drawn Anaglyphs', in ibid., p. 85.
24. Universität Stuttgart, Institut für Leichte Flächentragwerke, ed., *IL 9: Pneus in Nature and Technics*, Information of the Institute for Lightweight Structures (Stuttgart: Karl Krämer, 1977), p. 5.
25. Antoine Picon, 'Architecture and the Sciences: Scientific Accuracy or Productive Misunderstanding?', in *Precisions: Architektur zwischen Wissenschaft und Kunst*, ed. by Ákos Moravánszky and Ole W. Fischer (Berlin: Jovis, 2008), p. 71.
26. Institut für Leichte Flächentragwerke, *IL 9*; Institut für Leichte Flächentragwerke, ed., *IL 19: Growing and Dividing Pneus*, Information of the Institute for Lightweight Structures (Stuttgart: Karl Krämer, 1979).
27. Frei Otto, 'Das Ästhetische', in Institut für Leichte Flächentragwerke, *IL 9*, p. 19.
28. Institut für Leichte Flächentragwerke, *IL 21*, p. 17.
29. Ibid., p. 16.
30. As one researcher wrote, the use of digital models 'must not necessarily be derived from a material model; it may be determined by calculations on the basis of certain geometric characteristics of the desired surface [...] In the case of the Munich tent roofs, the digital presentation was simple because the supporting construction is defined by the x,y,z coordinates of the cable junctions.' Institut für Leichte Flächentragwerke, *IL 6*, p. 83.
31. Mathias Kutterer and Bernard Vaudeville, 'Maquette', in *Art De L'ingenieur: Construction Entrepreneur Inventeur*, ed. by Antoine Picon (Paris: Editions du Centre Pompidou, 1997), p. 278, author's translation.
32. Ibid. It is for this reason that Vaudeville and Kutterer argue that measurement models would eventually have to be supplanted by the 'virtual space' of informational calculation.
33. Fritz Leonhardt, quoted in Nerdinger, *Frei Otto: Complete Works*, p. 227.
34. Universität Stuttgart, Institut für Leichte Flächentragwerke, ed., *IL 16: Tents*, Information of the Institute for Lightweight Structures (Stuttgart: Karl Krämer, 1976), p. 138.
35. Universität Stuttgart, Institut für Leichte Flächentragwerke, ed., *IL 8: Nets in Nature and Technics*, Information of the Institute for Lightweight Structures (Stuttgart: Karl Krämer, 1975), p. 275.
36. Soap models, incidentally, were only used for part of the Olympic roofing, and most of the forms of the cable net structures could not be described as minimal surfaces. This was one of many deviations from Otto's theory of lightness that occurred during this process. Mick Eekhout, 'Frei Otto and the Munich Olympic Games', *Zodiac*, 21 (1972), 12–73 (p. 27).
37. Institut für Leichte Flächentragwerke, *IL 8*.
38. This setup, we are told, consisted of: eighteen Linhof cameras that took double-exposure photos to show net deformations and record stress gauges; miniature cameras recording protractors to see mesh angle displacements; strain gauges showing vertical displacement; and wire strain gauges showing forces. Mention is also made of 'electric pickups' and 'automatic recording', but it is not entirely clear what this means. Ibid.
39. Klaus Linkwitz, 'Photogrammetric and Computational Work for the Olympic Roofs, Munich', *Zodiac*, 21 (1972), 76–81 (p. 77). Incredibly enough, an error of 0.007 mm in the model could result in a cable being 0.8 mm too long or too short, which when stretched would become 5 cm, which would mean that the tension would be off by 50%. Eekhout, 'Frei Otto and the Munich Olympic Games', p. 45.
40. Klaus Linkwitz, 'Photogrammetric and Computational Work for the Olympic Roofs, Munich', *Zodiac*, 21, p.77.
41. Argyris was an aeronautical engineer at the University of Stuttgart. He is known as one of the pioneers of Finite Element Analysis (itself based on early theories by the same mathematician, Richard Courant, whose soap film experiments were a source for Otto). The Finite Element method was developed and applied at a large scale for the first time for the Olympic Roofs.
42. Marios C. Phocas, 'John Argyris and his Decisive Contribution in the Development of Light-Weight Structures: Form Follows Force', *Proceedings of the 5th International Congress on Computational Mechanics (GRACM 05),* held in Limassol, Cyprus, June/July 2005 (Nicosia: Kantzilaris Publications, 2005).
43. Linkwitz, 'Photogrammetric and Computational Work for the Olympic Roofs'.
44. Eekhout, 'Frei Otto and the Munich Olympic Games', p. 54.
45. Sanjay G. Reddy, 'Claims to Expert Knowledge and the Subversion of Democracy: The Triumph of Risk Over Uncertainty', *Economy and Society*, 25.2 (1996), 247.
46. Ibid.

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Daniela Fabricius is a historian and theorist of architecture and urbanism. Her current research focuses on questions of rationalism, economy and calculation in postwar West German architecture. Her writing has been published in *Architectural Design, Journal of Architectural Education, Harvard Design Magazine, Stadtbauwelt,* and *Log*. She teaches at the Pratt Institute.

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