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Models in civil engineering from ancient times to the Industrial Revolution

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1.1 Introduction

At the outset of this book, it will be useful to consider the difference between architectural and engineering models for the design and construction process. Architectural models have been documented since antiquity as showpieces or votive objects. In terms of content they represent architectural spaces, their creative design and sometimes the use of the enclosed or/and surrounding areas. Even if they may sometimes present elements related to the structural design, their main focus is still the design and shape of the space. Due to their attractive and often curious design and their use as showpieces and votive objects, many of them have been conserved until our times. It is only since the Renaissance, however, that construction-related (mechanical) models, began to be helpful not only for architectural, but also for structural design and hence this time marks the beginning of technical models as we know them today. These models for structural design fulfilled a new task in the design and planning process: they helped to visualize, explain, test or simply propose technical solutions for construction problems which could not be described or resolved using words or drawings alone. Their use was primarily experimental and less representational and were thus more ephemeral than their architectural counterparts. Their fundamentally practical use is probably one of the reasons why so few of them are still conserved, but also their use for experiments leading to failure was not always helpful for ensuring their conservation. If technical models were used for competitions, usually only the winning proposal has been preserved, not the discarded ones.

The different purposes for which these specific historical models were built comprise a large range, including: testing (new) mechanisms and designs, checking mechanical functioning and structural behaviour (stiffness, strength, rigidity and robustness), demonstrating the viability of new ideas, or new proposals to convince the clients to give their approval, exploring and confirming how the machines etc. should be constructed – the design of connections, the sequence of assembly, learning how to build full-size works, including apprentice 'masterpieces', and to demonstrate to visitors and potential clients how things

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worked. They have also been built for competitions and for patents, and because they were required as a part of construction contracts.

Many scientists and constructors described the use and the utility of physical models as tools for empirical cognition. Their manuscripts, together with contemporary publications from the times of Leonardo da Vinci (1452-1519), Galileo Galilei (1564-1642) and later, can be taken as a possible starting point. The writings of Leon Battista Alberti (1404-1472) and authors of many subsequent treatises on mechanics, structural design and architecture play an important role in the establishment of models as tools for testing and teaching construction techniques during the following centuries. During the Age of Enlightenment, associated with the emerging industrial revolution, the use of engineering models increased and documentation about their use improved. This process lasted during the early experimental phases of new technologies until the techniques became well-established – together with the testing of materials – in the practice and the education of engineers towards the end of the Industrial Revolution into the early decades of the nineteenth century.

Our understanding of the use of models for mechanical and construction solutions since the Renaissance has recently been growing more than ever before through the discovery of original drawings, manuscripts and publications, and also a growing number of surviving physical models have been discovered. Today we find the traces of them spread throughout archives, historical publications, museums and local collections, often still awaiting further research, thorough study and greater appreciation of their role in engineering.

1.2 Engineering models in classical times

The earliest evidence for the use of models in engineering design and construction is to be found in two manuals for military engineers (*Belopoeica* – On artillery) dating from around 250BC. One was written by Philon of Byzantium (c.280-c.220BC); the other was written by Heron of Alexandria (c.10-c.70AD) but he acknowledged what he wrote was largely taken from lost treatises by Ctesibius of Alexandria (c.300-222 BC) [1]. Both Philon and Heron discuss the use of experiments to determine the best dimensions to use when making artillery with a certain performance requirement (size of projectile and range). The power of a catapult was determined by the diameter (D, in *dactyls*. 1 dactyl = c.19.3 mm) of the elastic spring (twisted sinews). For a *euthytone* catapult, this diameter was calculated as one ninth of the length (L, in *dactyls*) of the metal-tipped wooden arrow – i.e. $D = L/9$. This design rule allowed the dimensions of a small catapult to be scaled up for use in building a larger one – a smaller one effectively served as a model for a larger one. No detail was given of the range of sizes for which this scaling process was valid [2]. Philon and Heron both give a more complicated relationship for the larger *palintone* catapult, able to throw stones weighing many tens of kilograms. The diameter D, in dactyls = $1.1 \times \sqrt[3]{(100M)}$, where M is the weight of the stone projectile in *minas* (1 mina = c.0.44 kg). Knowing the diameter of the spring, D, the design rules that Philon and Heron describe also give all the other dimensions of at respective catapults, such as the length of the catapult arms, the size of components of the timber frame, and so on. The dimension, D, called the *module*, is thus the single dimension needed to specify the entire design of a catapult.

The Roman engineer and architect Marcus Vitruvius Pollio (exact dates not known, c.70 B.C.-c.10 A.D.), who trained as a military engineer, included similar design rules for catapults in his book *De architectura*, compiled around 30-15 B.C. He cited both Philon and Ctesibius as his sources [3]. However, Vitruvius went a significant step beyond Philon and Ctesibius in giving the first clear description of using technical models in antiquity, again in the field of military engineering. In the tenth book of his *De architectura*, he recounts an exemplary story about the military engineers Diognetos from Rhodes, Callias from Aradus and Epimachos from Athens, who had to construct a military device for their King Demetrius. He discusses the advantages and disadvantages of both small-scale- and full-size models (Latin: *exemplaribus*) and notes that some dimensions in a model can be scaled up linearly to full size, while others cannot [4] (see Appendix A.1).

After the classical era, apart from some evidence of models for mill technology in the late Middle Ages, the earliest evidence of the existence of technical scale models, built in parallel with architectural ones, emerged in around 1400 [5]. One of the earliest documents refers to a competition for the design of a stone-saw for the builders of the cathedral of Milan in 1402, when a scale-model of the winner's proposition was built in wood in order 'to be able to try it out' [6].

1.3 The Master Builders of the Renaissance and their engineering models

1.3.1 Phillipo Brunelleschi and Florence cathedral

One of the oldest technical models is documented for the year 1418: it is Filippo Brunelleschi's (1377-1446) model of the cupola of Santa Maria del Fiore in Florence, which demonstrates an innovative bricklaying technique (It.: *Spinapesce*, Eng: herringbone) that permitted the cupola to be constructed without a supporting scaffold that was usually necessary for arch and dome constructions [7]. Although the scale of the model has not been documented, we know that he used regular bricks to build it and that the model could be examined from inside – indications of a large scale. With this proposition he had emerged as the winner of a contest seeking the best solution for the construction of the cupola. Ten models had been presented and their costs contribute an interesting fact to the practice of model making at this time: The range of their costs rises from 2 florin + 8 lira up to 127 florin + 510 lira: the latter was for Brunelleschi's model [8]. These costs illustrate the enormous range of quality that these models could offer, and their great economic value for the architects. Brunelleschi appreciated the use of models for both architectural and technical solutions and built many models of scaffolds and cranes [9]. However, his model from 1418 was not the only one he built for the Florence cupola: another, dating from around 1420, is still conserved in the *Museo dell'Opera di Santa Maria* *del Fiore* in Florence and illustrates their plainness. Recent measurements of this 1:60 scale model have proved at the same time the precision of its manufacture [10].

Models were also used for other important competitions, as for example in the one tendered for the construction of the crossing tower (It.: *Tiburio*) of Milan Cathedral in around 1490. Since the master builders of the fifteenth century were both architectural and structural designers, their treatises also attached great importance to the use of scale models as an additional resource for architectural and for technical planning and presentation. They could be helpful additions to drawings and written descriptions for their customers, the local approval authorities and the craftsmen during the building process. Filarete (Antonio di Pietro Averlino, 1400-1469), Leon Battista Alberti (1404-1472) and Francesco di Giorgio di Martini (1439-1501) explicitly mentioned them as essential means of architectural and technical representation and research in the planning process, and recommend checking the results of different means of presentation against one another. Martini also discusses modelling in the context of mill technology because drawings and written explanations were not able to explain technical contexts as well as mechanical models. Models also served as three dimensional plans for the reproduction of technical devices [11].

1.3.2 Leonardo da Vinci

In his book *Lives of the Most Excellent Painters, Sculptors, and Architects*, first published in 1550, Giorgio Vasari (1511-1574) praises, as the first among the many ingenious skills of Leonardo da Vinci (1452-1519), his creativity as a designer and model builder for 'tunnel boring machines, leverages, winches and screws for lifting heavy loads or to tow them away and [his proposals] in which way port basins can be cleaned or water can be elevated from the greatest depths by means of pumps' [12]. Leonardo himself was no less modest about his capacities as a model builder when he proposed, in his letter of application [13] to Lodovico il Moro (1452-1508) shortly before his arrival in Milan in 1482, presenting models of his inventions in Lodovico's park or any other space. Nevertheless, it is questionable whether Leonardo, with his own limited resources, really would have been able to afford the building of these expensive models to an acceptable quality. The only model we know he constructed was an architectural one, when he participated in the competition for constructing the lantern of the cathedral in Milan between 1487 and 1490. It was a wooden model, accompanied by a series of drawings [14]. We do not know whether his masterful drawings of machines and instruments for construction or his many sketches of testing devices for building materials and structural behaviour were based on real experiments using models, or not: some writers think they were [15].

It was only at the end of the nineteenth century, when Leonardo's technical drawings first appeared in facsimile, that engineering historians first began to interpret them by means of models. When the first generation of models, initially shown in 1939 in the *Palazzo dell'Arte* in Milan, had been lost because the ship transporting them to Tokyo in 1942 sank, a second generation of models was created in 1952 and exhibited from 1953 in the *Museo Nazionale della Scienza e della Tecnologia* in Milan in commemoration of the 500th anniversary of Leonardo's birth. However, the technical difficulties encountered when trying to construct accurate models of Leonardo's inventions from his drawings which, at first glance appeared perfect, suggest that his sketches were not really made for this purpose [16].

1.3.3 Andrea Palladio

In the second half of the sixteenth century, the use of models in architecture and civil engineering seems already to have been established to such an extent, that Andrea Palladio (1508-1580) does not mention them in this treatise *The four books of Architecture*, first published 1570 in Venice. Nevertheless, Palladio commissioned two models, paid for by the city council on 26 October 1569 [17], for the construction of the timber bridge over the Brenta river in Bassano di Grappa in order to support his carpenters who prepared and assembled the construction. Two years earlier, in 1567, his expert opinion had been in demand for the evaluation of a model for the cathedral in Brescia [18] which was surely not the only occasion when he had dealt with his own and other master builders' models as part of the general procedure in planning and building. There are further allusions in Palladio's and later in Claude Perrault's (1613-1688) writings that they used scale models of timber bridges for scaling dimensions for the real construction. More than a century later around 1750 the engineer Bartolomeo Ferracina (1692-1777) rebuilt Palladio's bridge at Bassano and manufactured a wooden model of a pile driving machine that he used on the site: this model is still conserved in the *Museo di Storia della Fisica* in Padua [19]. These facts suggest again the proliferation of models for engineering and construction purposes both for display and on the construction site, and the demand of models of hoisting devices, pumps, cranes, weirs, etc. for engineering and building competitions increased considerably towards the end of the seventeenth century.

1.3.4 Domenico Fontana and moving the Vatican obelisk

The most famous construction competition at this time was announced in 1585 by pope Sixtus V to find an engineer to undertake the moving of the so-called Vatican Obelisk. This announcement motivated many Italian and other European architects and engineers to present their proposals and ideas with plans, descriptions and models in a spectacular meeting with the pope and his administration in Rome. The winner of the contest was the engineer in charge of constructing St. Peter's Basilica, Domenico Fontana (1543-1607). His narrative of the project was published in 1590 entitled *Della Trasportatione dell'Obelisco Vaticano […]* [20] and the first illustration in this work shows eight models that had been submitted in the competition, each with a short explanation. (Figure 1.1)

This illustration takes us to the place where the Vatican Obelisk (Fontana calls it *Guglia*, a spire) had stood since the Roman Emperor Caligula (reigned 37- 41 AD) had it erected in the central spine of the *Circus Gai et Neronis*. This site in 1586 was an open space adjacent to the old St. Peter's church just behind the

Figure 1.1 Fontana's illustration of nine models of methods for raising the Vatican Obelisk. His own is shown at the top of the page. (Source: [20] p. 7)

sacristy and apparently served as the place where the models were presented. In the background the construction of the new St. Peter's can be seen and from a cloud in the upper right corner Minerva (Pallas Athene), the Roman goddess of wisdom and crafts with a bundle of rods in her arms, with an olive branch emerging from one of them, observes the scene with curiosity. Fontana's model is identified by an 'A' and elevated towards heaven by two putti. Fontana presents his model at the top, drawing it larger than the others, and comments: 'A. The first one, which was accepted and executed which will be explained in this book'. The remaining models are all at a scale of around 1:10 (2.5 m tall, based on the size of the adjacent people) or 1:5 (5 m tall, based on the drawing of the full-size obelisk) and are positioned on the ground around the obelisk. They were all observed by two members of the Vatican's committee who are comparing what they see with the current literature. On the ground in front of them lies a wind rose, which serves to highlight the scientific standing of the models. Fontana comments on them as follows: 'B. The second, which was to support the spire just with slight ropes on the top. C. The third, which wants to balance [the spire] on a half wheel. D. The forth, which wants to establish [the spire] using only wedges. E. The fifth, which wants to lower [the spire] using screws, and to carry it inclined, as they say, half in the air. F. The sixth, which wants to establish and lower [the spire] with a single bar in the form of a steelyard. G. The seventh, which consists of a half wheel, upon which they want to lower [the spire] tooth by tooth, like the buckets of a millwheel. H. The eighth, which wants to establish, lower, and pull [the spire] by the power of screws.' In order to elevate his own solution – as the putti do in the drawing- the alternative proposals are shown as not very feasible and their description rather dismissive.

Fontana's systematic and well-organized procedure for calculating the physical geometry and the loads involved, drawing elevations, and resolving the transport and placement of the obelisk, establishes him as perhaps the first engineer to work in a modern scientific manner. The purpose of his book is not only an early-published presentation of using engineering scale models and a documentation of the methods he employed, but also a science-based instruction for further tasks and future engineers.

One more scientist of the sixteenth century cannot be omitted: Galileo Galilei (1564-1642), came to fame not only by his 'Discorsi…' and his telescope, but also thanks to his mechanical experiments with models. He received a privilege based on a model of a water-lifting device that he presented in Venice in 1594 [21]. Only a few decades later Robert Hooke (1635-1703) and Christopher Wren (1632-1723) used, for the first time recorded, a hanging chain model (catenary) to help define the optimal structural form for the cupola of London's St. Paul's Cathedral (see Section 3.2.1).

1.3.5 The Fleischbrücke: a case study in technology transfer

The close trading relations between Northern Italy and Southern Germany and the visits to Venice, Florence, Milan, and elsewhere by German master builders such as Elias Holl (Augsburg, 1573-1646) and Joseph Furttenbach (Ulm, 1591-1667), stimulated an intense technology transfer between Italy and Germany in the late Renaissance. A striking example is the case of the construction of the Fleischbrücke in Nuremberg in 1598. There is no doubt that the master builders in Nuremberg knew about the construction of the Rialto Bridge in Venice. The winning design of a spectacular competition in 1551 was famous for its innovative construction, and was built by Antonio da Ponte (1512-1597) between 1588 and 1591. This was just a few years before the planning of the Fleischbrücke began. The similarity between the two bridges concerning their structural challenges and their solutions is clear: both are designed to cross the river with a single flat, segmental arch (Rialto Bridge, 28.8 m span and Fleischbrücke, 27 m); both required careful design of the timber centring, and both had their foundations in very marshy ground [22]. Although it is clear that there has been some technical exchange from Venice to Nurenburg, a study of the original documents in Venice and Nuremberg do not reveal a direct influence by the Venetian designers on the German bridge. It seems most likely, therefore, that there was a personal exchange of experience [23], and the strongest evidence for this is the existence of a model.

Wolf Jakob Stromer (1561-1614), who was Nuremberg's chief master builder between 1595 and 1598, commissioned and supervised the planning and building of the Fleischbrücke. His descendants today still own a curious model of the Rialto Bridge which had recently been completed (constructed 1588-1591). The model is not dated but was already in Nuremberg when the Fleischbrücke was being built. However, as it is not mentioned in either the Nuremberg or the Italian archives [24], it cannot have been used for the design or construction of the Fleischbrücke. Nevertheless it is a remarkable piece that is conserved in its original wooden case in the private archives of the Stromer family in the castle of Grünsberg near Nuremberg. The painted wooden model, without a declared scale (65.5 x 23.4 x 29.1 cm, approximately 1:70) represents the complete Rialto Bridge, fixed on a two-piece baseplate, including abutments and centring. [25] The model consists of fifteen pieces and can be disassembled (upside down) into these pieces: first the buildings on top of the bridge can be removed, and then the arch below and the centring; finally, the whole model can be separated into its individual pieces. As a special feature there is a drawer in one abutment which shows a cross section through the foundation of the bridge. This three-dimensional model

Figure 1.2 Model of the Rialto Bridge, conserved in the Stromer family archives, Grünsberg Castle, near Nuremberg. (Image: [26])

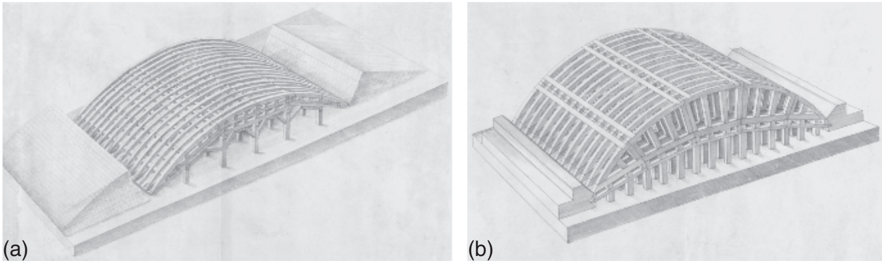

Figure 1.3 Two prints, dated 1595-1603, showing models of designs for the timber centring for the Fleischbrücke, Nuremberg. (a) Probably the adopted solution. (b) An alternative, heavier solution. (Image: Courtesy of Staatsarchiv Nürnberg. Stromer-Archiv [28])

demonstrates beautifully the main challenges of the original design for the bridge and an approach to their solution: it was clearly intended to be an instructive device. (Figure 1.2)

The documentation of the Fleischbrücke revealed the existence of two other models produced at the time when the bridge was under construction: both models are lost, but two drawings of them, and related documents still survive (Figure 1.3). The models show two possible solutions for the timber centring used for the erection of the main arch. They were probably made to find the best possible construction of this essential and difficult element. It is likely that the final solution is that shown in Figure 1.3a [27].

1.4 The first collections of engineering models

The increasing number of technical models produced during Renaissance stimulated local rulers, building authorities and academies, from the second half of the sixteenth century, to collect these objects for the purpose of documentation in their archives. Architects and engineers, who were gradually joining the emerging bourgeois elite in society, also began to assemble collections of models in their Cabinets of curiosities (*Wunderkammer*) [29].

For instance, already in 1532, the city council of Nuremberg recognized the value of their building models, including models of mills and particular construction elements, and brought them together in a new secure space in the town hall, specifically designed to house the collection, having previously been dispersed in the armoury and several other locations [30]. Shortly after its installation, the town hall of Nuremberg presented a temporary exhibition of mechanical models in 1569, which may have been the first of its kind [31]. Half a century later, in 1620, the city council of Augsburg established a model chamber in its new town hall that would later become well known (see Section 1.3.1).

The German architect Joseph Furttenbach (1591-1667) in Ulm mentioned in the foreword of his treatise *Architectura Civilis*, published in 1628, that an architect must be capable, not only of drawing plans, but also of producing explicitly 'scale models made of timber' of his constructions [32]. In later years Furttenbach installed a *Kunstkammer* (cabinet of curiosities) in his own house in Ulm and, in

1641, published another treatise, *Architectura Privata,* dealing particularly with the design of this house and the collection presented there, illustrated with additional explanatory plates showing models of bridges, construction equipment and water-raising devices [33]. Amongst the many other objects, he included models of different kinds of mills and also important waterworks, all of them listed and described in his book. He mentioned proudly that his models included also a cutaway model ('one shoe high') of the rope winch used by Fontana in 1586 for the translocation of the Vatican's obelisk, and improved by Galilei in 1617. We do not know if he really met Galilei in his *Grand Tour* of Italy between 1606 and 1617, but he claims to have received the model of an endless spindle or winch from Galileo's own hands, which was, of course, displayed in his collection.

Thanks to a catalogue, published in 1683 and distributed not only in France, but also in Britain and Germany and maybe elsewhere, we learn about one of the first public exhibitions of mechanical models [34]. The author of the catalogue is not explicitly mentioned but it was most likely to have been Jean Baptiste Picot (dates unknown), quartermaster during the reign of Louis XIV, who was in charge of organizing the exhibition under the patronage of the then superintendent of buildings and later Grand Master of Ceremonies, Jean Jules Armand Colbert, Marquis de Blainville (1663-1704) [35].

As Colbert and Picot adhered to a rigorous experimental rationalism, this exhibition was intended to encourage engineers and inventors to use models to present their inventions, rather than relying only on drawings or written descriptions, and probably also to promote technical inventions within France [36]. The exhibition consisted of twenty-one models with indications of their scale, manufactured by diverse workshops. Twelve of these models were explained and illustrated with plates in the catalogue. Most were of mill machinery such as timber mills, drilling equipment for cannons, and numerous water-lifting devices. Some of the models represented machinery already published in treatises by authors such as François Beroald (Lyon 1578), Georg Andreas Böckler (Nuremberg 1601) and Salomon de Caus (Frankfurt am Main 1615) in an improved and technically more convincing version. Eight of the models were by two French inventors: of Jean Baptiste Picot, the curator of the exhibition and author of the catalogue, and M. Tarragon, a somewhat unknown artisan. Without going into further details of such models, it can be confirmed that, by the end of the seventeenth century, the interest in and use of engineering models had become ubiquitous and common knowledge in Europe, and their utility motivated more and more engineers to build them in order to confirm the correct function of their inventions, as well as to promote their acceptance and use.

1.4.1 Elias Holl and the Augsburg model chamber

The Free Imperial City of Augsburg has collected design models and models of record of important building projects since the early Renaissance. In 1620, Elias Holl (1573-1646), Augsburg's most famous architect and designer of its new town hall (built 1609-20), turned the room above the Golden Hall into a dedicated model chamber. The Augsburg collection was one of the first to focus not only on architecture, but also on what would come to be known as civil engineering. This original collection was augmented by additional engineering models donated later by the St. Anna grammar school, a protestant educational institution with firm humanistic and scientific aspirations. The school was founded in 1531, and located in the courtyards of the St. Anna Carmelite monastery, which was dissolved in 1534. Between 1613 and 1615 the school built an additional building, designed by Elias Holl, alongside the old one; both are still remaining. Scientific instruments and mechanical models were collected there for educational purposes.

Another well-known collection of models was later incorporated into the city's model chamber. These were models of the hydraulic engineering works of Caspar Walter (1701-1769) which he had installed in the water towers of Augsburg (see Section 1.3.2). The model chamber in Augsburg later incorporated several bridge models from the former Building Museum, which was part of the local Building School, founded in 1893 in the former monastery of the Holy Cross. Today, 126 models are listed in the inventory of the municipal model chamber including fourteen models of bridges, eight models of machinery and construction equipment, twenty-five of waterworks such as pumping stations and water towers, sixteen of mills, seven of roof trusses and one of a scaffold. Two models are of double and triple helix staircases, seven represent the city gates and eight more show the towers. The model chamber also has eight models related to Holl's historic, surviving town hall: the old town hall (1515-1516); a second Italian model (1609); a Palladian model (1611); model I by Holl (1614); a three-gable model by Holl (1614); model II by Holl (1614); a roof crossing, model III by Holl (1614/15); a Venetian model, model IV by Holl (1614/15); and a model of the floor structure for the town hall [37]. There is also a model of a boat and six miscellaneous models with mainly architectural content.

One of the oldest models in the model chamber represents the *Lueg-ins-Land-Turm*, an observation tower and part of the city wall. The model was made in 1514 by the carpenter and sculptor Adolf Daucher (c.1460-1523/24) to present the architectural and structural design of the tower (Figure 1.4).

Perhaps the most spectacular models of Augsburg's architecture are two models of the entire city, the older one dating from 1563 (Figure 1.5) and the other from the seventeenth century.

Even if, as we have already seen, Elias Holl's idea was not really new, nevertheless, his particular selection of models for his collection makes it so very remarkable. In his time, Holl, a traditional type of master builder for those days, was appreciated more for his technical and engineering achievements than for his architectural designs, which are what are generally admired today [40]. Son of a master builder family for two generations and a master mason by training, Holl was appointed as the city's 'master builder' in 1602 and took this opportunity to rebuild the flourishing city of Augsburg. His oeuvre ranges from civil and religious architecture to engineering projects such as bridges, canals and mills. In his personal family chronicle, it is with some pride that Holl himself mentions his successful solutions to structural and technical problems rather than his architectural designs [41]. Among the many drawings and written documents

Figure 1.4 Model of the 'Lueg-ins-Land Tower' by Adolf Daucher manufactured in 1514. Modellkammer in the Maximilianmuseum in Augsburg. (Image: Dirk Bühler [38])

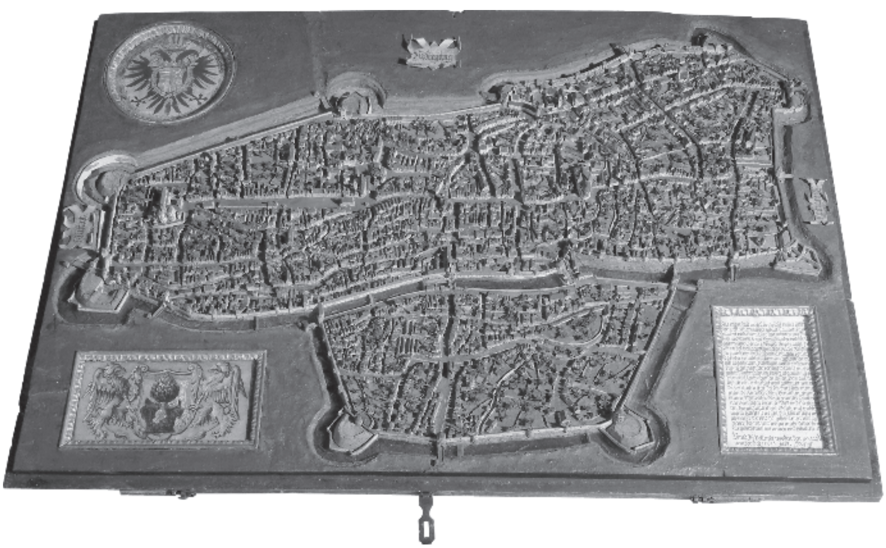

Figure 1.5 Model of the city of Augsburg made in 1563 by the master printer Rogel after three years of survey and wood-carving work. (Image: Courtesy of Kunstsammlungen und Museen Augsburg [39])

still conserved in the city and other archives there is an illustrated manuscript of 209 folios, entitled 'Master Holl's Book of Drawings'. It deals formally with 'geometry and the art of measurement', and contains not only a compound treatise on geometry, surveying and the related instruments, but also precise indications about building materials, their composition and practical application, together with tables of their measures and weights [42]. This valuable document, probably intended for later publication, is a reliable and valuable source for deepening our knowledge of Renaissance construction methods. Based on his built legacy, his written and drawn documents, and contemporary sources, we know that Holl was constantly engaged in designing innovative construction equipment and collected models of both his architectural and engineering achievements.

After Elias Holl had received the commission to design and build the new city hall, and before the old Gothic building could be demolished, the precious bell hanging in the old town hall had to be relocated to the nearby Perlach Tower between 1614 and 1615. After confirming the stability of the tower's structure, Holl proposed an additional roofed space on top of the tower to accommodate the bell. For this task he planned a scaffold surrounding the tower and a special crane. This scaffold was a self-supporting structure independent of the tower's wall and without the use of clamps, thus protecting the façade from damage, as Holl explained in his chronicle [43]. This technically demanding task is represented by one his most important models - still conserved - in the model chamber, together with his extraordinary architectural models of the town hall. Holl mentions that he delivered several models to the city council at that time, but without further specification of them we do not know if the scaffold model was made before or after the construction and hence we cannot be sure about its use. Other models from Elias Holl's time include a lifting device for the gentle handling of cut stones (Figure 1.6), a crane with a worm gear, moveable in two directions, and an automatic ram. Later models include the scaffold used for the vaulted ceiling of the St. Anna grammar school (1747), the architecture and the timber roof truss of the Schrannenhalle, and a covered market hall close to St. Moritz church (1750).

1.4.2 Caspar Walter and hydraulic engineering in Augsburg

The second great contribution to Augsburg's model collection relates to hydraulic engineering. Founded by the Romans in the first century BC, during the reign of Emperor Augustus, on a mound surrounded by the rivers Lech and Wertach, Augsburg has always had a plentiful supply of fresh water, but the careful management and distribution of running water was not common until the late middle ages. In 1412, the city council built the first pumping station to feed the newly-installed public fountains. From that time, the city had at its disposal a double hydraulic infrastructure: a grid of canals providing the mills with hydropower, and a network of wooden water pipes fed by the pumping station at the 'Rotes Tor', one of the main city gates. With the establishment of its first waterworks, Augsburg became an international exemplar for urban water supply, and the city soon installed a collection of models and explanatory panels in the new water towers for interested travellers who came to learn from the 'Brunnenmeister' (master of the waterworks).

Figure 1.6 Model of an innovative lifting device (17th century), Modellkammer in the Maximilianmuseum in Augsburg. (Image: Dirk Bühler [44])

Caspar Walter (1701-1769) had been Brunnenmeister in Augsburg since 1741 and, in 1754, he published *Hydraulica Augustana* in which he described the three central water towers, the well houses of the waterworks with all their technical installations, and expanded the model collection displayed in the main tower [45]. Walter's description begins on the third floor of the main tower, where several crankshaft models are presented. On display on the fourth floor are models of weirs, dams and sluice gates suitable for installation in canals and rivers. Other models illustrate the use of stone, bricks and timber in the construction of basins, gates and pit lining. There are even models of a canal bridge, a boat used when stabilising river banks, and several roof frameworks. Visitors to the fifth floor see a number of text panels, five models of Augsburg's famous pumping stations, a model waterwheel driving three different types of machinery, as well as water towers, well houses, and a mill driven either by muscle power or hydraulic power. Also on display, with a description, is a model of the sluices and weirs along the branch of the Lech River known as the 'Hochablass' which conducts water into Augsburg's canal system. The exhibition culminates on the sixth floor, with three large models of pumping stations. Different types of transmission shaft show additional practical uses of hydropower. The presentation is completed by a series of panels, showing the water distribution system and all its technical installations. The seventh floor – where a small stairway leads to the viewing platform on top of the tower – contains the water tank. The models that Walter describes were made to present the technical achievements of Augsburg's water infrastructure, and for educational purposes in his workshop – many of the models were masterpieces made by his apprentices.

The distribution of fresh water to the public fountains and households in Augsburg created a need for bored timber pipes for the supply system. Such pipes – straight tree trunks up to four metres in length that were drilled using a borer with an iron cutting head – had been well-known since Roman times and used in many places, even until the end of the nineteenth century. The making of these pipes posed two main challenges for the workers. The first was how to keep the cutting head, which was usually fixed to the end of a wooden or iron rod, straight while steadily drilling through the centre of the trunk. The second challenge was to provide enough human or mechanical power to carry out the drilling, which required considerable energy. In this context, the functional model of an eighteenth-century timber pipe-drilling machine (Figure 1.7) deserves particular consideration because it illustrates clearly how the power transmission provided by the waterwheel, and the labour-saving gears, are combined into a horizontal, water-powered drilling machine to perform the task. This practical machine pulls and fixes the trunks in position so that they can be drilled easily. Aside from a few drawings published in artisan treatises, this is the only three-dimensional representation of this kind of machinery. The model can be operated with a crank handle to move the waterwheel.

Two of the twenty-five hydraulically-powered machines are outstanding examples [47, 48]. The first is an eighteenth-century model of a pumping station, formerly exhibited in the main tower of the Augsburg waterworks and described by Walter. The model represents two water pumps, each consisting of three hydraulic cylinders. The devices were operated by a waterwheel placed between them. Water pipes conduct the water to the tank on top of the tower (not represented in this model) (Figure 1.8). The main difference between the two pumping devices lies in the power transmission between the waterwheel and the pumps: in one model, the transmission is performed by a cumbersome swinging beam; in the other, a more modern transmission is achieved by means of a cranked shaft.

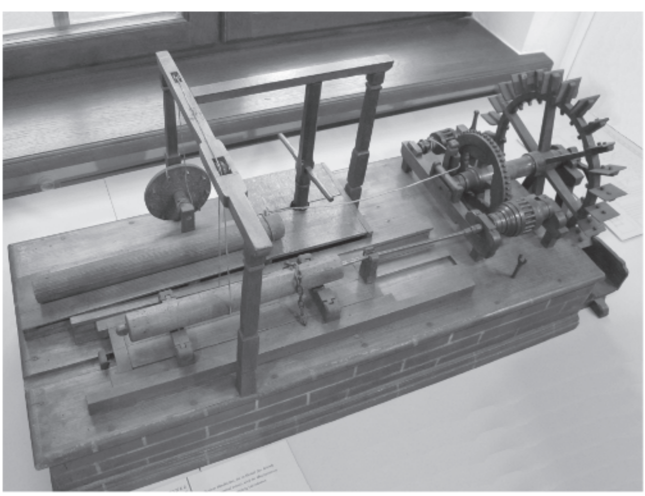

Figure 1.7 Model of a boring machine, driven by a waterwheel, for making timber water conduits, Maximilianmuseum in Augsburg (Image: Dirk Bühler [46])

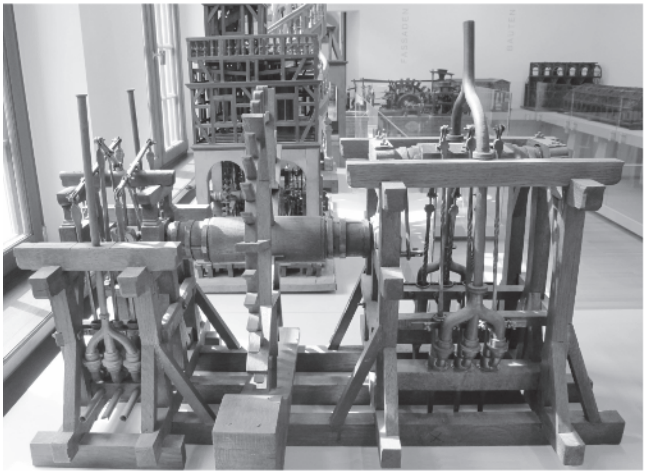

Figure 1.8 Models of two water pumps made by Caspar Walter in 1754, Maximilianmuseum in Augsburg (Kunstsammlungen und Museen Augsburg, Inv.-Nr. 9753) (Image: Dirk Bühler)

The model thus displays the transmission technologies used at the turn of the sixteenth and seventeenth centuries (the swinging beam) and the more modern transmission, introduced during the eighteenth century (the cranked shaft).

The second remarkable model demonstrates several possible uses of hydraulic power. As the brass label on the base plate states, it was made by the carpenter Andreas Seuffert in 1758. It shows a central waterwheel surrounded by seven mills with sixteen different types of gear. The waterwheel can be turned by a hand crank to demonstrate the operating mode of mills and gears. This sophisticated and functional teaching model was used by its manufacturer for presentations at various courts. The mills and their corresponding mechanical devices include a flour mill, fulling mill, paper mill and an oil mill on one side of the waterwheel, and sawing, hammering and polishing mills on the other side. This well-constructed model is able to convey the state-of-the-art milling techniques in the mid-eighteenth century, and is a precious technical document of its time.

Caspar Walter was not only an important hydraulic engineer and *Brunnenmeister*; he had also trained as a master carpenter and bridge builder. In his treatise on bridge construction [49], published in 1766, he described all types of bridge and their construction details, and includes some discussion on models. For the first time he described how he deduced from a load test on a wooden model at a scale of 1:20, the dimensions and load capacity of the real bridge, using direct proportion. However, Walter was mistaken in this interpretation of the results of a model test. Leonard Euler (1707-1783) read Walter's publication and explained the mistake before going on to discuss, for the first time, the non-linear scaling of bending behaviour in models of structures (see Chapter 4).

Finally, there is an interesting insight into professional relationships in hydraulic engineering in the eighteenth century. When the pumping station for the great fountain in the ducal gardens of the Nymphenburg Castle near Munich had to be replaced in 1767, the Bavarian prince-elector Maximilian III

Joseph (1745-1777) did not consult the famous hydraulic engineer of the nearby Imperial City of Augsburg. Refusing his bourgeois ambience, he looked out in his own aristocratic circles for a French pump engineer, successfully trained in the ducal gardens of Lunéville, considered as a second garden of Versailles. He contracted Jacques Faye Poitevin (life dates unknown), a travelling pump engineer, who worked between 1767 and 1786, most of his time successfully, in Nymphenburg [50]. Documents in the archives indicate that Poitevin was required to build a model of his pump to demonstrate how it functioned, unfortunately not conserved or described in detail.

1.5 Models in the Age of Enlightenment

1.5.1 Cabinets of curiosities

From the beginning of the eighteenth century an innovative approach to mathematics, physics, mechanics and engineering, based on rational experiments, grew and flourished among scientists and engineers. This new approach enhanced the status and prospects of existing scientific academies and promoted the foundation of new ones. A central activity of the academies was the scientific experiment, realized by demonstrations and by means of models; this practice also led to larger collections of original equipment and models used for representing the behaviour of full-size reality as well as for illustration, documentation and education. At the same time, more and more private amateurs began collecting mechanical devices and scale models for their Cabinets of mechanical curiosities as a symbol of their wealth and learning [51]. Perhaps the best-recorded *Cabinet de curiosités* was created in Paris in the 1730s by the amateur scientist Joseph Bonnier de la Mosson (1702-1744) and comprised many thousands of objects. The largest of the nine rooms was devoted to mechanical devices and included models of machines powered by clockwork, a coin press, various machine tools, a machine to desalinate seawater, another for desilting ports, a machine to transplant trees, a water pump motor, machines to help on construction sites (one from Fontana), machines from various mills (for pressing sugar cane, paper, grain, etc.). There were also many pump models, several cranes, a model of a bridge that could be built quickly, Archimedean screws, a horse-powered grain threshing and winnowing machine, and two dynamic model paddle-boats [52]. Meanwhile, in Britain, the collection of Archibald Campbell, the first Earl of Islay and third Duke of Argyll (1682-1761) became famous for the variety and quantity of objects, which included models of improvements for agricultural machinery. Both collections were sold and scattered after the death of their owners. Also in Britain, King George III (1738-1820) established his own collection starting in 1760 with the appointment of George Adams (1750-1795) as his Mathematical Instrument Maker and initiator of his collection. This collection contained engineering models too, and is largely conserved today in the Science Museum in London.

The first scholastic Cabinet of Physics was created for the first time in Europe in 1675 at the University of Leiden after experiments were introduced into science education. The scientific exchange stimulated the creation of similar collections, mainly in the second half of the eighteenth century, in Stockholm and Uppsala, Florence and Padua, Lisbon and Coimbra, Vienna and Munich, Prague, Oxford and London.

The collection of the University of Oxford includes a number of significant objects from civil engineering. The original Museum was built between 1679 and 1683 in order to host the collection of Elias Ashmole (1617-1692) and developed constantly to a considerable size, mainly after 1714 when demonstrations began to accompany the lectures. The collection today is embodied in the University Museum. A catalogue from 1790 lists a model of a machine for breaking pieces of wood, models of cranes, pile drivers, pumps and mills and even 'Smeaton's pulley with a three legged stand' [53]. Instrument and model makers such as Benjamin Cole (1695-1766) and Edward Nairne (1726-1806), scientists such as Jean Desaguliers (1683-1744) and Stephen Demainbray (1710-1782) left their legacy to today's University Museum in Oxford and the Science Museum in London. It was Demainbray who designed models of water lifting machines, waterwheels, pile drivers and other helpful construction devices in order to use them for his famous lecture-demonstrations.

Another remarkable collection of models encompassing civil engineering applications was established in the Netherlands by Pieter Teyler van der Hulst (1702-1778). After his death, the Teyler Foundation decided, in 1779, to construct a Museum for his collection. When the Museum opened in 1784 in Haarlem, it presented not only usual mechanical demonstrations, but also devices of particular relevance to typical Dutch hydraulic construction problems including hoists, cranes, pile-drivers, polder mills, a saw mill, a bucket dredger, a water-lift and a lock gate.

By the end of the eighteenth century engineers and constructors realized that models represented a marvellous means for promoting their products. The completion of the Iron Bridge at Coalbrookdale, built between 1777 and 1779 and opened to traffic in 1781, was the first cast-iron bridge in Europe. As such, it was considered one of the wonders of the age and was promoted as a spectacle. Only a few years after the opening, in 1787, the ironmaster and constructor of the bridge, Abraham Darby III (1750-1789), ordered a model of his exemplary bridge to be assembled by his ironworks foreman and patternmaker Thomas Gregory (dates unknown). The intention was to donate it to the Royal Society in order to promote his engineering work and his enterprise in its famous collection [54]. The model was built at an impressive scale of 1:24 (with a span of 1.2 m) and presented to the Society in 1787, where Darby proudly received a gold medal for his much-appreciated gift. After some repairs and mounting in a glass display case, the model was added to the collection of the Society, and is still conserved in the Science Museum in London [55].

1.5.2 The models of Hans Ulrich Grubenmann

In October 1755 the carpenter Hans Ulrich Grubenmann (1709-1783) presented a model of his proposed bridge over the river Rhine to the city council of Schaffhausen in Switzerland [56], planning to construct a single span of 119 metres, the largest timber arch ever built up to that time. After several previous requests in larger cities in Germany and inquiries within the scientific community, the city council decided in August 1755 to invite Grubenmann to present his proposal, even though he was neither the scientist nor the engineer they had been looking for, rather 'just a carpenter'. Grubenmann was already well-known in Switzerland for his timber roof structures and bridges. It was said that, when the councillors doubted the stability of the construction, Grubenmann placed himself on top of the model with the famous words: 'If the model supports me, the real bridge will support several carriages' [57]. On the one hand, this suggests that the model could have been made for an empirical test of its strength and stability, in which case Grubenmann would have been one of the first constructors to use a model for such a practical test or demonstration. On the other hand, this episode obviously did not take into account that there can be great differences between the structural behaviour of the model with respect to the real construction, a problem which already had been mentioned by Vitruvius and already in the mid-eighteenth century, was understood as the 'state of the art' in engineering. Nevertheless, the explanation of his structural design finally convinced the councillors to accept one essential change: the bridge should be built with an additional pier in the centre of the span. Recent examinations of the structure suggest that the decision to build an additional pier was not so much due to mistrust of the stability of the construction, but rather due to the additional timber needed for the larger span [58]. The construction of the bridge was completed only three years later and contributed to Hans Ulrich Grubenmann and his family achieving international fame.

Since Schaffhausen was at a crossroads for international travellers, many visitors started to write about this and other bridges by the Grubenmann family. Mathematicians, architects and engineers commented on the construction, copied his plans and published and distributed them in Germany, France and Britain. One of the most famous was Sir John Soane (1753-1837) who visited Schaffhausen in 1780 and studied the bridge thoroughly, copied the plans, completed them with his own drawings and used these documents for his lectures as examples for other architects and engineers [59]. In 1833 he set up a museum in his home in London to present his collection of architectural, archaeological and structural curiosities to his clients and students. Apart from his important collection of Canelatto's paintings (including bridges) he also displayed cork models of some buildings in Pompeii and, a wooden model of a pile driving machine, dating from around 1754 that Soane had purchased in 1801 [60]. Drawings of Grubenmann's (and other) wooden bridges are still conserved in the museum's archives [61]. Even the renowned French engineer Jean Rodolphe Perronet (1708-1794) collected drawings and probably a model of a Grubenmann bridge [62].

Today there exist six models of Grubenmann bridges dating from their time of construction, of which four are confirmed as being made by Grubenmann: the Schaffhausen Bridge (around 1755); the Wettingen Bridge (around 1765); the bridge in Stein (around 1760); and the so called 'Trogen Bridge' (around 1745-1755, real site unknown) (Figure 1.9) (see Section 39.2.1). These models are unique remains of the original bridges. Grubenmann made them mainly to work out their complex construction and to instruct his own workers.

Figure 1.9 Original model of the 'Trogen bridge' (around 1745-1755), Grubenmannmuseum, Teufen, Switzerland. (Image: Dirk Bühler)

Along with various drawings and publications, Grubenmann's models served to raise awareness of his constructions throughout Europe. For example, they inspired others such as Konrad Altherr (unknown dates) from Chur and Johann Konrad Langenegger (1749-1818) from Gais in Switzerland, who built a model for a 300-metre timber arch bridge for a competition to cross the River Foyle in Londonderry, Ireland [63, 64] (see Section 4.2.2). The history of this design competition is told in different ways. The prize was probably awarded originally in 1771 by Frederick Hervey, Lord Bishop of Derry (1730-1803) for the design of a timber bridge that should span the river, '827 shoe-lengths wide', in 'one or two Schwibbogen' (i.e. spans) [65]. In 1770, inspired by the fame of the Grubenmann brothers' bridges, Hervey and the young architect Michael Shanahan (c.1731-1811) visited the Alpine countries and northern Italy and had engravings of various timber bridges drawn, presumably to determine a realistic basis for the construction of his timber bridge planned in Derry [66]. According to some reports the winner of the design competition was Johannes Grubenmann, although most report that the winner was Altherr. In 1772, he and two colleagues travelled from Appenzell in Switzerland to Londonderry with a 19-foot (5.8 m) long model of the bridge. An account in the Gentleman's Magazine noted that the journey that took them about five months, that the model comprised 11,734 separate parts and about 4000 screws, and that the bridge had 62 windows on each side [67, 68]. News of this competition and the model travelled to Russia where its description in the St. Petersburg Vedomosti (business report) corresponded to that given in the Gentleman's Magazine in 1772 [67] and its construction was attributed to Konrad Altherr. Remarkably, this model survives in the Science Museum in London (see Section 39.2.1). Altherr and Langenegger built two models later in the 1770s to promote Swiss timber bridge construction in St. Petersburg, Vienna and London.

1.5.3 The models of John Smeaton

John Smeaton (1724-1792) was a truly remarkable engineer and only came to civil engineering at the age of 29. By this time he had learned much in his father's workshop at home, had worked for four years as a maker of scientific instruments and, at the age of 28, had been elected as a Fellow of the Royal Society.

During the first half of the eighteenth century, energy efficiency was an issue that captured the interest of the scientific community across Europe, in particular, the relative efficiency of different types of generators of mechanical power – waterwheels and windmills. At this time, many eminent scientists were gaining great confidence in using theoretical science to justify claims about how the real world functioned, and water power was no exception. The French scientist, Antoine Parent (1666-1716), for example had stated in 1704, that an undershot waterwheel had a maximum efficiency of about 15% and that this was achieved when the rim speed was one third that of the water stream. Despite their errors, such views were widely accepted, for example by Bernard Forest de Bélidor (1698-1761) in his *Architecture Hydraulique* (1737), who went on to state that an undershot wheel was six times more efficient than the overshot type. John Theophilus Desaguliers FRS (1683-1744), on the other hand, claimed that the overshot wheel was ten times more efficient than the undershot type. Such statements had clearly been made without the robust evidence of experimental investigation. It was Smeaton who would tackle this question and resolve the 'monstrous disagreement' as Thomas Telford later called it.

Smeaton undertook his experiments on models of waterwheels (about 60 cm diameter, a scale of approx. 1:8) (Figure 1.10) and windmills (about 1.6 m diameter, a scale of approx. 1:5) (see Figure 24.1) in 1752-1753. From his model tests on waterwheels, among many conclusions, he found that overshot wheels were about twice as efficient as undershot wheels (66% compared to 30%) thus refuting the assertions by many of the scientific community [69]. Based on the understanding he gained from these experiments, he went on to work on over fifty water-powered mills and a several windmills.

Smeaton was well aware of the dangers inherent in scaling up the results of model tests to full size, and withheld publication of the results until 1759, by which time he had verified many of the design guidelines that followed from his experiments; he had designed and constructed several waterwheels, and carried out tests on full-size windmills, in which he changed the shape and angle of attack of the sails:

> 'What I have to communicate on the subject was originally deduced from experiments made on working models, which I look upon as the best means of obtaining the outlines in mechanical enquiries. But in this case it is very necessary to distinguish the circumstances in which a model differs from a machine in large; otherwise a model is more apt to lead us from the truth than towards it. Hence the common observation, that a thing may do very well in a model, that will not answer in large. And indeed, tho' the utmost circumspection be used in this way, the best structure of machines cannot be fully ascertained, but by making trials with them, when made of their proper size. It is for this reason, that, tho' the models referred to, and the greatest part of the following experiments, were made in the years 1752 and 1753 yet I deferred offering them to the Society, till I had an opportunity of putting the deductions made therefrom in real practice, in a variety of cases, and for various purposes; so as to be able to assure the Society, that I have found them to answer' [70].

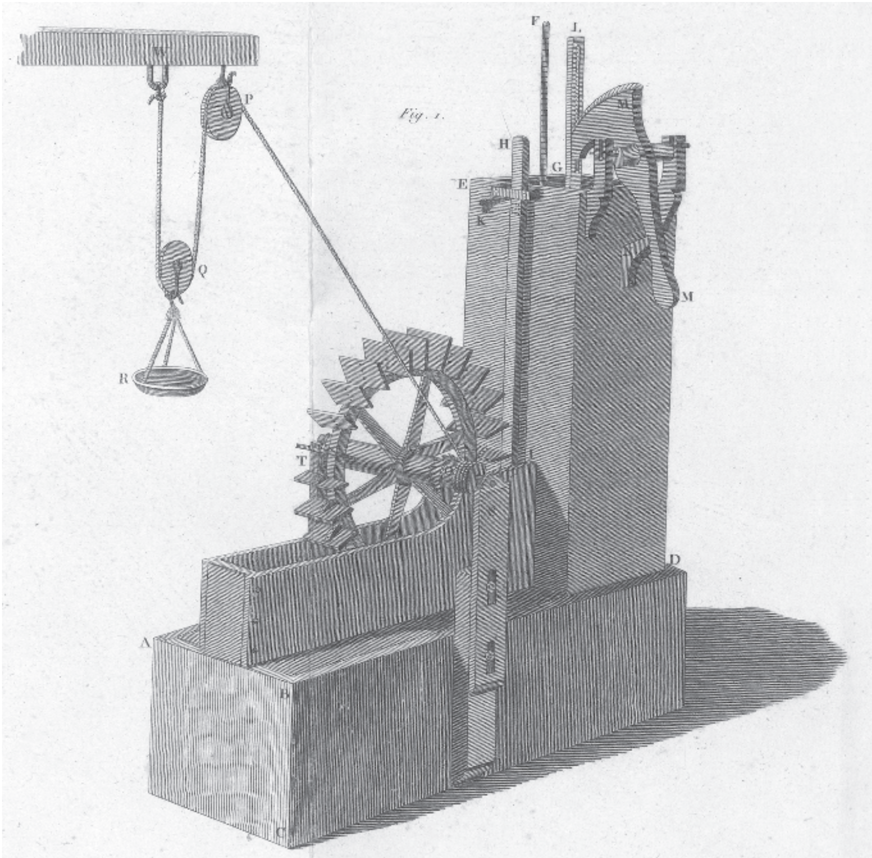

Figure 1.10 John Smeaton's model waterwheel used to compare the efficiency of an overshot and undershot wheel (Source: [70] Plate 4)

Smeaton's greatest project was the construction of a stone lighthouse upon the Eddystone rock, 20 km south of Plymouth. He received the commission in 1756 when he was just 32 years old, and it was his first civil engineering project. In order to design the foundation of the stone structure on the irregular-shaped rock, Smeaton made two models of the rock, one before cutting it to shape (Figure 1.11), and the other after. This enabled him not only to fully understand the geometrical nature of the interface, but also to get a feeling (in his hands) of the effectiveness of the bond created by the cut stones interlocking with the recesses in the rock. He went on to explain why he placed such importance in making physical models:

> 'It seeming therefore to be a first principle, to cut the rock as *little as we could help*; and for this end, to humour its irregularities as far as we could, so as to get a firm fixing for our work ; on this account it appeared necessary, as the first step to be taken (from the dimensions already obtained, and by the methods already specified) to construct a *complete Model* of

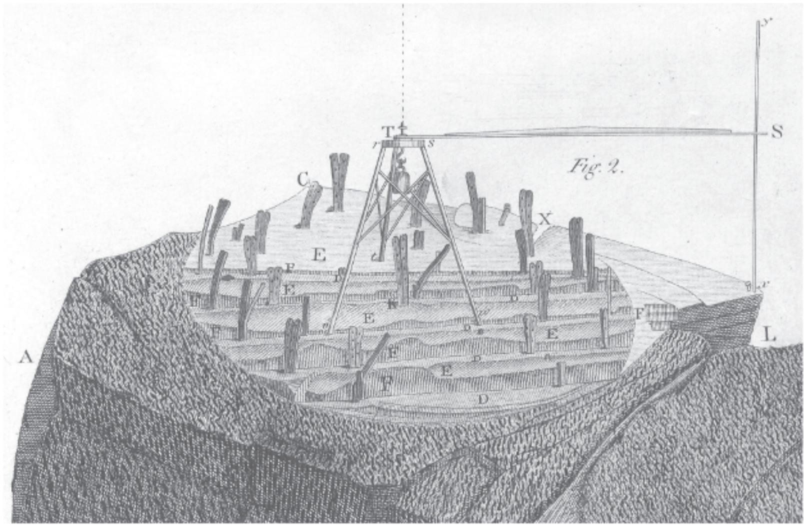

Figure 1.11 Smeaton's drawing of the model he made of the rough-cut Eddystone rock, used to determine how it would need to be cut precisely to receive the first five courses of cut stones forming the base of the lighthouse. (Source: [71] Plate 7)

> the rock, in the condition I found it : which being done, a second model might *then* be formed, shewing to what the rock was to be reduced, [...] These models I determined should be the work of *my own hands* ; and this I foresaw, must in its own nature be a work of *Time*.
> [...] I had also a further reason for undertaking this part of the work myself; which those who shall peruse this account for the sake of information, may not be displeased to know. I have always found in subjects of mechanical invention and investigation, that I can seldom form an original idea so complete, but that by laying it down in its proper dimensions on paper, I could very much mature and improve it ; and where the subject is attended with intricacy, it is in a greater degree necessary : but in reducing this to a *Solid*, as is the case in making a model, still further corrections and advantages will often present themselves, that did not appear upon *Paper* : and this in a much more eminent degree when the *Solid* is produced from the drawing by the artist's *own* hand, than by the hand of another ; and still further improvements will occur, by going again over the *detail*, in constructing the work itself at large. Therefore [...] I determined, from the paper materials that I had brought from Plymouth; as well as those I carried thither; at once to construct the models above-mentioned myself' [71] (spelling, italics and punctuation as original).

The cutting and placing of the stones for the lighthouse was supervised by Josias Jessop (c.1715-1761), father of the eminent canal builder, William Jessop. During the winter of 1756-1757 Jessop completed the drawings of each of the sixty-six courses of the structure and wooden models of the most important courses of masonry at a scale of about 1:16 (50 cm diameter), including Course VII, the first full course of interlocking stones, with the eighteen stone cubes serving as shear connectors between this course and the ones above and below [72].

Before reaching the detailed design and construction stages of the lighthouse, Smeaton had made much use of models in 'selling' his novel method of construction in the first place, among others to King George II. Later he made models to help to raise finance for the project and then to communicate to the backers of the project the changes he was proposing as the final scheme was developed. Smeaton continued to use the 1:48 scale model of the final design to publicise the structure, which had attracted great public interest. Indeed: 'so great was the curiosity of the public, at the completion of the present building, in the year 1759; and such were the numbers, by the intercession and recommendation of friends, that for some years after, flocked daily to see the model; that, to avoid having the whole of my time consumed in satisfying their curiosity, I found myself under a necessity of deputing Mrs. Smeaton, to shew and explain the model' [73].

1.6 Final remarks

This overview of early engineering models, from antiquity until the beginning of the industrial revolution, describes the enormous efforts engineers made to resolve mechanical and structural problems using physical models, and the obstacles they had to overcome to obtain useful results. In early times the focus of employing these models was mainly on military devices. Master builders, many of them coming from a military training, soon recognized the utility of engineering models for the design of civil and religious constructions and, since at least the beginning of the fifteenth century, have continued to benefit from this approach. The main uses of models were for devising machines that reduced manual workload, optimizing the efficiency of mechanical devices, determining the bearing capacities of structures, and resolving construction problems. Gradually, physical findings helped the engineers to perfect their methods and to create common rules for improved structural models.

The chapter has presented a base upon which were built the great advances in using models during and after the industrial revolution. It provides a vital point of departure for the appreciation and validation of the later development of physical models. In order to deepen these traces of the past and to improve their visibility and recognition in the public eye, the discovery, conservation and presentation of engineering models need to become a focus for future research into the history of engineering (see Chapter 39).

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