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WHY DRAW PICTURES OF MACHINES? THE SOCIAL CONTEXTS OF EARLY MODERN MACHINE DRAWINGS

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INTRODUCTION

Early modern machine drawings long have been studied with the purpose of reconstructing details of the machine technology employed in their age of origin.[1] In this context, two distinct groups of sources traditionally have received broad attention and by now, for the most part, have been edited: the numerous manuscripts by Leonardo da Vinci and the representational machine books. From the late Middle Ages the latter served to present spectacular engineering designs to a broader public, first in manuscript form and then in print. Regarding the reconstruction of early modern machine technology, the investigation of both Leonardo's machine drawings and the designs of the machine books always has been confronted with one central problem: It is often difficult to determine clearly the realizability of the designs presented. Thus, research on these sources long has focused on efforts to differentiate more clearly which of their designs represented machines actually in use in the early modern period and which of them should rather be regarded as products of the contemporaries' imagination.

Which role was assigned to the medium of drawing by early modern engineers themselves? And what effects did the employment of drawings have on the communication of existing knowledge and the production of new knowledge on contemporary machine technology? Such questions about the practical as well as cognitive functions of the means of representation used by contemporary engineers have been focused on more closely only recently. This is true for the drawings considered here as well as for three-dimensional models of machines.[2] This delay corresponds to the fact that even today, sixteenth-century engineering drawings with more practical functions, preserved as single sheets or personal sketch-books, are to a great extent unpublished and thus less accessible.[3] This chapter places special emphasis on such

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1 The topic of this chapter has been presented to a workshop at the Max Planck Institute for the History of Science (Berlin) and a *Journée des Études* at the Centre Koyré (Paris). I am grateful to the participants for their commentaries and suggestions, in particular for the extensive discussion by Pamela O. Long. An earlier version of this chapter has been published as "Maschinenzeichnungen der 'Ingenieure der Renaissance'" in *Frühneuzeit-Info* 13(2002), 1–21.

2 See Ferguson 1992, Hall 1996, Lefèvre 2003. For the related topic of the visual representation of the trajectories of projectiles, see Büttner et al. 2003. For the early modern employment of scaled-down models of machines, see Popplow (in press).

3 In the pioneering study by Ferguson (1992) on visual thinking in the history of engineering, Leonardo's manuscripts and presentational machine books are the only sources from the fifteenth and sixteenth centuries.

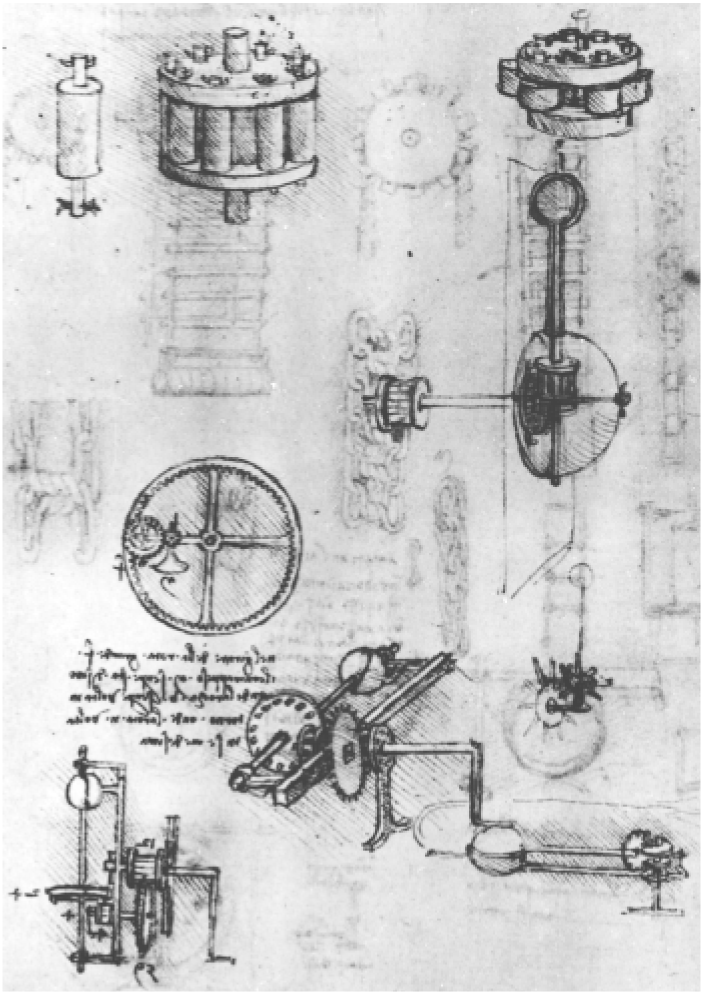

Figure 1.1. Studies of machine elements. It remains unclear whether the drawing documents thought experiments or objects actually assembled in the workshop. Drawing by Leonardo da Vinci. (Photo: Biblioteca Nacional Madrid, Codex Madrid, fol. 10v.)

less formal drawings not addressed to a broader public. It is such sources that document how the medium of "drawing" was indispensable for planning, realizing, and maintaining large-scale technological projects in the early modern period.

The aim of this chapter is to work out a classification of the contexts in which early modern machine drawings were employed.[4] This task confronts a number of difficulties regarding the interpretation of corresponding source material. For Leonardo's machine drawings, it long has proved difficult to determine the purposes they originally served (figure 1.1). Some have been identified as proposals for innovations of specific mechanical devices, for example, his series of drawings on textile machines (figure 1.2). Others have been interpreted as didactic means of conveying his tremendous knowledge on the behavior of machine elements to others, and some obviously served theoretical functions.[5] It furthermore has been suggested that Leonardo used drawings for recording trials with three-dimensional objects made in his workshop.[6] As regards the wealth of machine drawings preserved from early modern authors other than Leonardo, it has been argued convincingly that these must be differentiated according to their functions of documentation, communication, or design.[7] However, confronted with the source material considered below, which early modern engineers employed in the process of realizing mechanical devices, it has proved extremely difficult to assign precisely these functions to such drawings. With regard to these difficulties of interpretation, a different approach is taken here. As a first step, sixteenth-century machine drawings are differentiated according to four main contexts of employment: First, they served to present devices to a broader public; second, they could take on a role in the concrete manufacturing process; and third, they could constitute part of an engineer's personal archives. Fourth, and this final group to some extent amounts to a special case, engineering drawings could merge into or be connected with considerations of a more theoretical nature. Of course, such a classification does not exclude

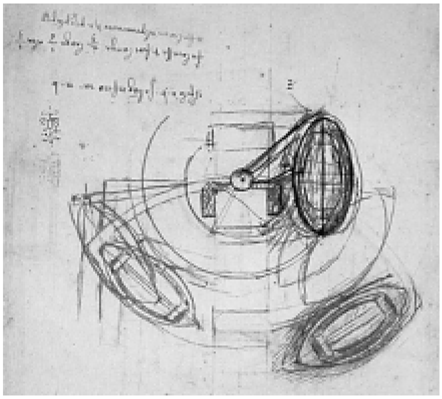

Figure 1.2. Detail of machine for weaving braids. Drawing by Leonardo da Vinci. (Codex Atlanticus, fol. 884^{r}.)

4 For a classification of medieval technical drawings, see Knobloch 1997.
5 See Truesdell 1982, Maschat 1989, and Long (this volume).
6 See Pedretti 1982 and Long (this volume).
7 See Lefèvre 2003.

the possibility that one and the same drawing could be employed in more than one of these four contexts over the course of time.

The following remarks are limited to describing the situation in the sixteenth century without investigating the question of the origins of the employment of machine drawings for more practical purposes in the Middle Ages. With the exception of the numerous illustrated gunners' manuals,[8] early engineering drawings from the fourteenth and fifteenth centuries have been preserved almost exclusively in the context of the production of presentational manuscripts. However, it is hard to imagine that the numerous fifteenth-century manuscript machine books could have been produced without any foundation in some less formalized practice. Scattered textual evidence that still awaits closer investigation indeed testifies to a more informal employment of machine drawings as early as the beginning of the fifteenth century.[9] Furthermore, it must be noted that any attempt to explain when and why drawings came to be employed in mechanical engineering in the Middle Ages must take into consideration the tradition of late medieval architectural drawings.[10] As the different roles of machine builder, architect, and fortification engineer emerged more clearly only in the course of the sixteenth century, it can be assumed that the employment of such a crucial medium as drawing in earlier periods still showed similar characteristics in all three of these fields.[11] As the focus of this chapter lies on the social contexts of employing machine drawings in the sixteenth century, neither will the development and use of different graphic techniques—most prominently, changes induced by the invention of perspective in the fifteenth century—be investigated here.[12]

1. PRESENTING DEVICES TO A BROADER PUBLIC

The above-mentioned machine books in manuscript[13] and in print[14] served to present machines to a broader public, formally continuing a manuscript tradition dating back to Antiquity and the Arab Middle Ages.[15] This public initially consisted of courtly audiences before expanding ever more to learned laymen and fellow technical experts during the sixteenth century. Drawings and later woodcuts and engravings allowed

8 See Leng (this volume).
9 Documents from the *fabbrica* of Milan cathedral mention in passing that proposals for a mechanically driven stone-saw were to be submitted first in the form of a drawing before the most promising designs were required to be presented as scaled-down models. See Dohrn–van Rossum 1990, 204–208.
10 See Lefèvre (this volume).
11 Contexts of employing architectural and fortification drawings in the early modern period have received only scarce attention to date. See Schofield 1991 and Frommel 1994a. Architectural treatises from the fifteenth century onwards often contain explicit discussions of the role of the medium of drawing in the design process. See Thoenes 1993.
12 See Ferguson 1992, Lamberini (in press), and Camerota (this volume). For the density of information conveyed and the broad variety of graphic techniques employed in Leonardo's machine drawings, see Hall 1976b; Heydenreich et al. 1980; and Galluzzi 1982. The argument brought forth by Samuel Edgerton, according to which geometrically constructed perspective drawings in sixteenth-century machine books paved the way for the "geometrization of nature" in the "Scientific Revolution" has, by now, been refuted convincingly. See Mahoney 1985 and Hall 1996, 21–28.
13 See Hall 1982a, Hall 1982b, Galluzzi 1993, Galluzzi 1996a, Friedrich 1996, Leng 2002, Long 2001, 102–142, and Leng (this volume).
14 See Keller 1978, Knoespel 1992, and Dolza and Vérin 2001.
15 See Lefèvre 2002 and Hill 1996.

these audiences to study siege engines, mills, water-lifting devices, and other examples of early modern machine technology. In the fourteenth and fifteenth centuries, these manuscripts contained mostly military devices. Well-known examples are the manuscripts assembled by Guido da Vigevano (c. 1335), Konrad Kyeser (1405), Mariano Taccola (1449), Roberto Valturio (1455, printed in 1472), and the author known as "Anonymous of the Hussite Wars" (c. 1470/1480). The first pioneering manuscripts showing engines for civil purposes were composed in Italy, again, by Mariano Taccola (c. 1430/1440) and Francesco di Giorgio Martini (c. 1470/1480). While large devices for military and civil purposes had existed only rather vaguely in the visual memory of medieval contemporaries, this situation now changed, at least for those among whom these manuscripts circulated. With the regard to the works of Konrad Kyeser, Mariano Taccola, and Francesco di Giorgio Martini, some dozens or even hundreds of copies of the original manuscripts have been discovered. They still await closer investigation concerning the questions of who commissioned them and who was responsible for the artistic process of producing the manuscript copies.[16] Towards the end of the sixteenth century, with the printed machine books of Jacques Besson (1578), Jean Errard (1584), Agostino Ramelli (1588), Vittorio Zonca (1607), Heinrich Zeising (1612ff), Salomon de Caus (1615), Jacopo Strada (1618), and Giovanni Branca (1629), machines for civil purposes became a subject of learned knowledge as well. In addition to the printed *Theatres of Machines,* a number of manuscripts have been preserved, which very likely document a preparatory stage of publication. One example is a manuscript version of Jacques Besson's "Theatrum instrumentorum et machinarum" (1571/72), which was later published posthumously.[17] The intention of publication also can be presumed in the case of a manuscript of the Florentine scholar Cosimo Bartoli (c. 1560/70),[18] which already shows typical traits of machine books: complete views of devices as well as additional detailed views, carefully ordered text sections and labels of reference (figure 1.3).

Late medieval and early modern machine books all have a comparable structure: Full-page images of technical devices are each accompanied by a more or less detailed text explaining their general features. While these explanations often consist only of a few lines in the early manuscripts—in some cases, there are no textual explanations at all—in sixteenth-century works, the length of the explanatory texts grew considerably. This is especially true for the printed machine books. Yet to be investigated is the question as to whether this growth of textual information corresponded to a shift in the contexts of employment of these works. It is well possible that some authors of the earlier manuscripts assumed that the inspection of their manuscripts would be accompanied by oral explanations. Authors of the printed sixteenth-century works, in contrast, from the start had to presuppose a "silent reader" who had to be provided with more detailed explanations of the functioning of the devices presented.

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16 See Leng 2002 and Scaglia, 1992. For the manuscripts of Konrad Kyeser, see Friedrich 1996.
17 See Keller 1976.
18 See Galluzzi 1991, 223.

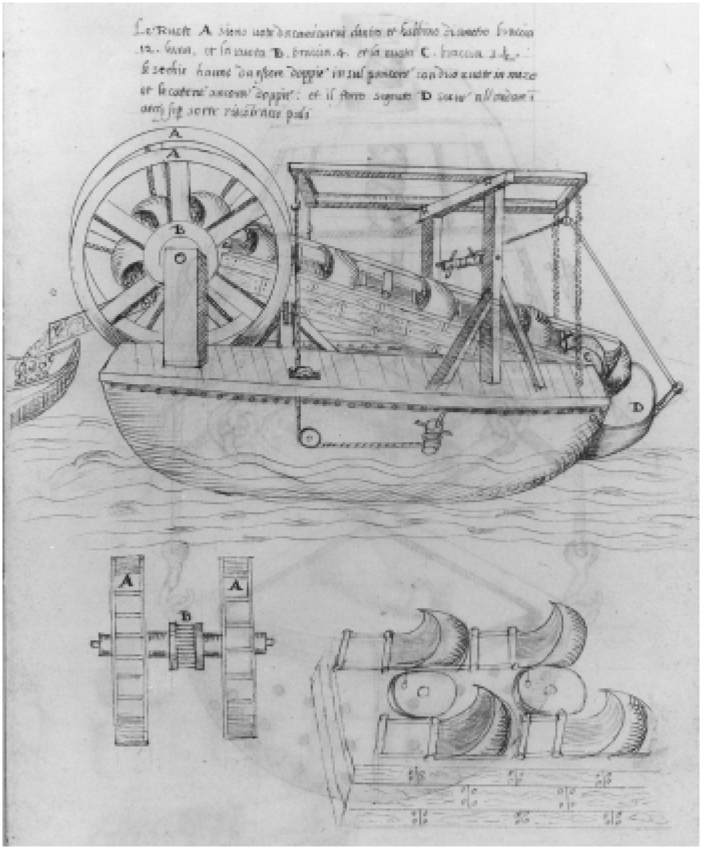

Figure 1.3. High-quality drawing of a dredger with didactic implications. Note the details of the mechanism drawn separately below. Drawing by Cosimo Bartoli, c. 1565. (Florence, Biblioteca Nazionale Centrale, Palatino E.B. 16.5 (II), fol. 60^{r}, courtesy Ministero per i Beni e le Attività Culturali, all rights reserved.)

Regarding techniques of graphic representation, the perspective illustrations in printed books on machines did not differ much from fifteenth-century presentational manuscripts: An elevated viewpoint enabled the spectator to discern machine elements that would remain hidden if the device were represented from the front on

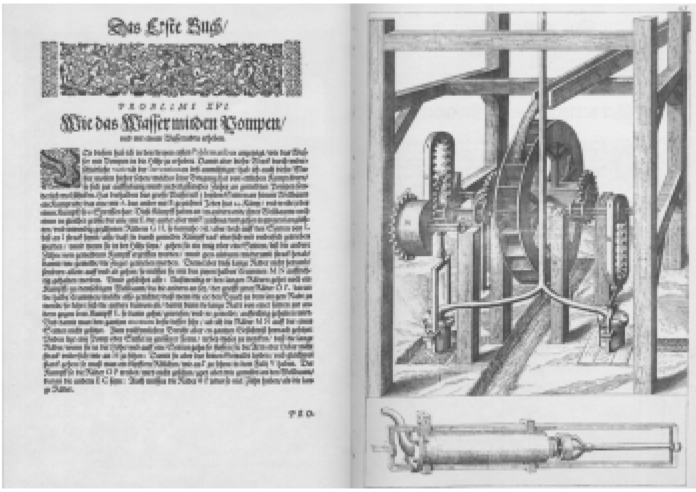

Figure 1.4. Presentation of pumps in a printed machine book. Below a separate drawing to emphasize technical details of the arrangement to drive the pumps' pistons. (Caus 1615, fol. 23^{r}.)

ground level. However, the perspective techniques now had become more refined. In continuation of fifteenth-century manuscripts, total views of a device were accompanied by separate drawings of technical details usually also rendered in perspective (figure 1.4). Other graphic techniques like horizontal or vertical sections or ground plans, more difficult to read for the lay spectator, are found only rarely in printed machine books (for a late exception, see figure 1.5).

It has often been stressed that representational manuscripts and printed machine books mirrored technical reality only to a very limited extent. Over time, however, this interpretation has changed considerably. In earlier research it was sometimes argued that the authors of these books did not yet dispose of modern exactness in their technological descriptions. More recently, such "playfulness" has been interpreted as a response to specific expectations placed on technical experts, especially in the context of court culture. From this perspective, early modern machine books appear as a distinctive genre characterized by a carefully selected information: "Unrealistic" designs in general might well be interpreted as expressions of anticipated future achievements. Usually, such designs represented combinations of machine elements, which themselves were already employed in practice. Indeed, authors of the printed machine books often stressed that the designs they presented also were to inspire their colleagues to try out ever new combinations of machine elements to improve traditional machine technology and to extend its fields of application. In this

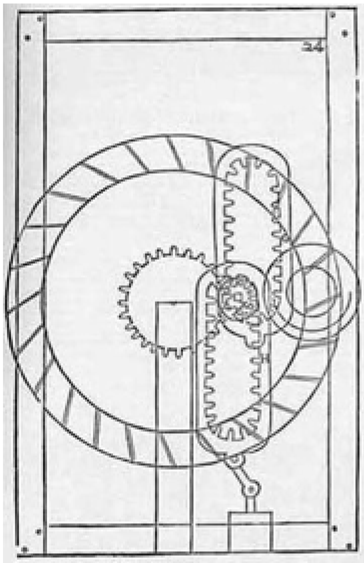

Figure 1.5. Vertical section of machine elements of the water-lifting device shown in figure 4. (Caus 1615, fol. 24[r].)

sense, the machine books could be ahead of their time without necessarily losing their relation to technical practice. A number of European territorial powers explicitly promoted the application of mechanical technology by granting privileges for the invention of newly designed mechanical devices.[19] This practice, which spread all throughout Europe in the sixteenth century, provides a very concrete background for the sense of experimentation conveyed by the broad variety of designs in the machine books.

Machine books served the communication between engineers and potential investors or interested members of the republic of letters, rather than that between engineers and artisans or workmen. The functions performed even by the late medieval manuscripts were manifold: They could serve to entertain or to present factual information, or to prove the erudition of princely commissioners and promote the self-advertisement of technical experts. Such implications of the practice of authorship in early modern engineering have only recently began to be investigated more closely.[20] Assembling textual and visual information on machine technology with the aim of presentation to others created a new kind of reflecting knowledge. This new kind of knowledge distinguished the engineer from the ordinary artisan and thus underlined the legitimacy of claims to higher social status of these technical experts.

Even though machine books served as a kind of visual inventory of contemporary technical ideas even among the engineers themselves, they played only a marginal role for engineers' everyday practice. The materiality of technology was often ignored in these presentational treatises. Machines in these books should be understood as a product of the engineer's brain, his *ingenium*; their material realization was not the topic of these books. The organizational activities of the engineer on the building site were mentioned as scarcely as materials, measurements or gear ratios—it was considered self-evident that such factors had to be established at a later point

19 See Popplow 1998b.
20 See Long 2001.

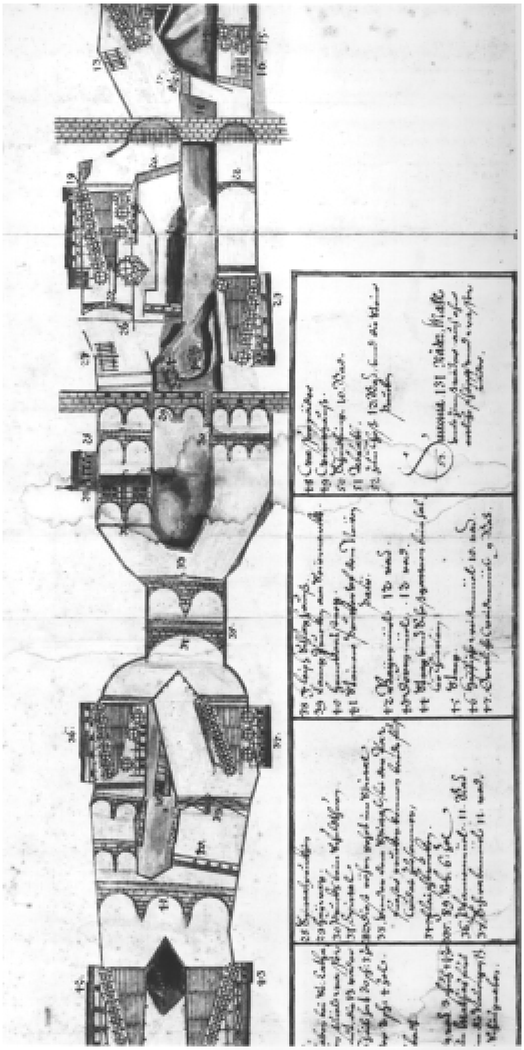

Figure 1.6. Survey plan by the town's master builder Wolf Jacob Stromer of the Nuremberg mills alongside the river Pegnitz (detail), 1601. (Photo: Germanisches Nationalmuseum Nürnberg, HB 3089, Kaps 1055h.)

of time at the site. However, illustrations of machines were often incorporated in lively landscapes or workshop scenarios to suggest the possibility of immediate employment.

Information on the process of creating illustrations for presentational treatises is scarce. For most of the earlier manuscripts, the persons known as "authors," such as Guido da Vigevano, Konrad Kyeser, or Roberto Valturio, were responsible only for the texts and the composition of the treatises and commissioned the production of the illustrations to artists who remained anonymous. The selection of these artists and how they were instructed about which devices they had to illustrate, and how and with which technical details, remains unclear. This is also true for the woodcuts and engravings in the later printed works. That artists visited each machine at its original site is documented, as an exception, in the case of Georgius Agricola's preparations for his encyclopaedia on mining, *De re metallica,* published in 1556. His letters show that he had to send different artists to the mining centres of Saxony several times until he found one who produced drawings of the machines employed there in a quality sufficient to serve as templates for the woodcuts.[21] It is difficult to imagine that this was a standard practice, however; artists sometimes might have drawn from three-dimensional models of machines or from some sort of sketch. In any case, the production process of such books on machines presupposes some tradition of more informal machine drawing, of which only faint traces have been preserved from the period preceding Leonardo da Vinci's notebooks.[22]

In addition to their incorporation in machine books, machine drawings with representative functions have also been preserved as single leaves. A special case is provided by plans kept in communal archives representing, for example, a town's waterways. From early fifteenth-century Basle, such a plan has been preserved with a coloured scheme of the different waterworks crossing the town. It is assembled of pieces of parchment and is, in total, nearly ten meters long.[23] In other cases, such plans also depicted water-mills alongside the town's waterways in symbolized form, that is, as mill-wheels turned ninety degrees laterally (figure 1.6).

A different example of a carefully composed machine drawing with representative functions has been preserved among the documents of Württemberg master builder Heinrich Schickhardt (1558–1635). It shows a device that had been built a short time earlier by the carpenter Johannes Kretzmaier, probably under supervision of Schickhardt himself, to provide the castle of Hellenstein near Heidenheim with water (figure 1.7).[24] Between the source and the castle, a height difference of a total of ninety meters had to be overcome. The drawing emphasized only the core element of the transmission machinery: a combination of a lantern and an oval rack. It served to transfer the rotary motion provided by the water-wheel to the reciprocating motion of the horizontal beam driving the piston rods of the pumps. Indispensable construction details of the device, like the guide rails of the rack, are missing. The lower part

21 See Kessler–Slotta 1994.
22 See McGee (this volume).
23 See Schnitter 2000.
24 See Müller 2000.

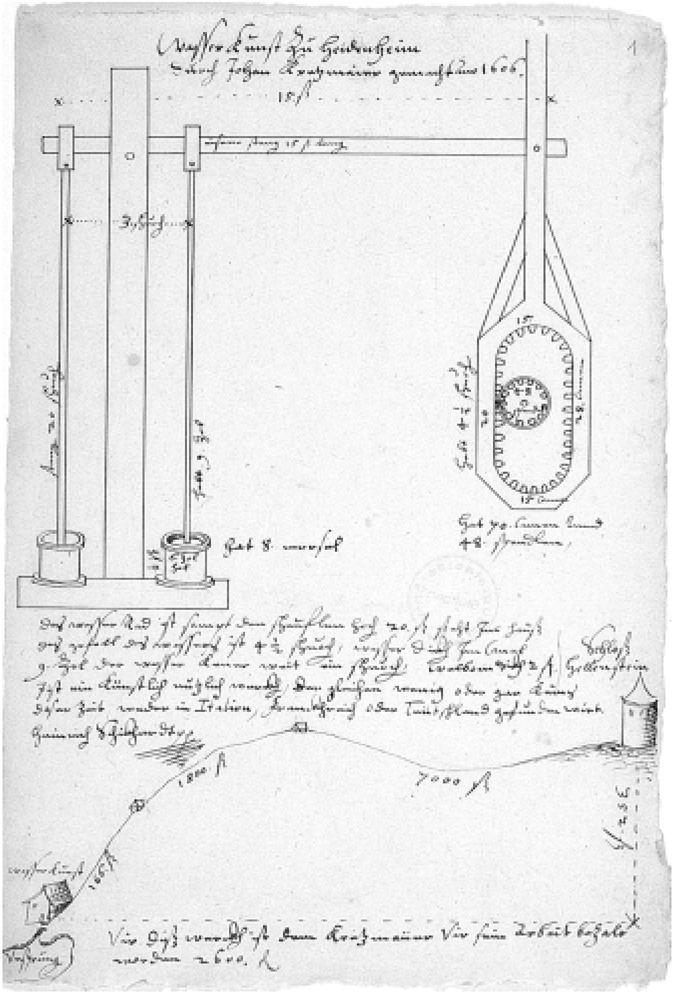

Figure 1.7. Commented presentational drawing of the pumps supplying Hellenstein castle. Drawing by Heinrich Schickhardt, 1606 or after. (Stuttgart, HStA, N220 T149, all rights reserved.)

of the drawing serves to visualize the concrete setting of employment: at the bottom left, the building that housed the device; above right, Hellenstein castle. In addition to specifications of measurements and the performance of the device, a written commentary signed by Schickhardt testifies to the documentary character of the sheet: "This is an artificial and useful device of which only few or even none are to be found neither in Italy, nor in France or Germany in these times."[25] The exact purpose for which this drawing had been produced nevertheless remains unclear.

2. MACHINE DRAWINGS IN THE PROCESS OF REALIZING MECHANICAL DEVICES

Starting in the late Middle Ages, the separation of the social roles of engineer and artisan became more clearly discernible. While the former was responsible for the design and the organization of a given project, the latter carried out the actual work. This development is discussed as one of the central prerequisites for the growing relevance of drawings to mechanical engineering since the late Middle Ages.[26] In the sixteenth century, in any case, drawings in the process of realizing mechanical devices served the engineer to communicate with the investor on the one hand and (although presumably to a lesser extent) with the artisans carrying out the work on the other.

Communication with the investor especially concerned the preparatory stage of realizing mechanical devices. With regard to the competition among early modern engineering experts, drawings could serve to present engineers' abilities at a foreign court, even though for such purposes the demonstration of scaled-down models presumably was preferred, because of the more immediate impression it created. Both of these media played a central role in the above-mentioned practice of granting privileges for inventions.[27] Applicants for such a privilege in a certain territory often submitted drawings or models to underline the credibility of their inventions. Such presentations, however, were not necessarily required, as in any case the inventor had to prove the realizability of his invention after the privilege had been granted by constructing a test specimen in full size in the course of the subsequent six to twelve months. In some cases, applicants presented a whole set of inventions by means of illustrated manuscripts, which ultimately strongly resembled manuscript machine books. This was true in the case of the above-mentioned manuscript by Jacques Besson, the designs of which were protected by a privilege in 1569 when the compilation was presented to King Charles IX.[28] A quite similar manuscript was composed in 1606 by the Spanish engineer Jerónimo de Ayanz for King Philipp III.[29] To obtain a privilege for inventions, Ayanz presented drawings of forty-eight of his inventions,

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25 "Ist ein künstlich nutzlich werckh, der gleichen wenig oder gar keins dieser Zeit weder in Italien, Franckhreich oder Teütschland gefunden wirt." Stuttgart, HStA, N220 T149.
26 See McGee (this volume).
27 See Popplow 1998b.
28 See Keller 1976, 76.
29 See Tapia 1991, 53–256.

most of which were presented as sketches in perspective and accompanied by extensive descriptive texts.

A manuscript composed with quite different intentions, under the supervision of Duke Julius the Younger of Brunswick-Wolfenbüttel around 1573, represents an attempt to employ catalogues of designs of mechanical devices for concrete regional innovations.[30] The manuscript assembled illustrations of devices and instruments that were to facilitate and speed up labor in the quarries and on the building sites of the duchy. Moreover, it contained a list of persons active in the duchy's administration and declared that they were obliged to consult the volume accordingly to improve the technical equipment available at the sites for which they were responsible. Some of the illustrations had been copied from earlier manuscripts, others show instruments reportedly already employed elsewhere in the duchy, and a few represent inventions allegedly made by Duke Julius himself (figure 1.8). While a number of formally similar manuscripts mentioned above seem to have been composed rather for reasons of prestige or entertainment at court, this manuscript was thus composed with the aim of practical employment. In this context, the designs of the Wolfenbüttel manuscript clearly refer to local circumstances in the Wolfenbüttel duchy, a trait that is not discernible in other cases. Attempts to turn designs encountered in such manuscripts into practice are, of course, quite conceivable in other cases as well, but they have not yet been documented. With the deliberate intention of realization after his death, the unique sketches of mills left behind by Nuremberg patrician Berthold Holzschuher were similarly meant to serve as a guideline to construction, although in a purely private context.[31]

In the concrete process of realizing mechanical devices, drawings helped the engineer to bridge the different locations of decision processes and the actual realization of a project—the court or the town hall and the building site. These contexts are especially easy to discern with regard to examples from the broad collection of some two to three hundred loose leaves containing drawings of all sorts of mills and water-lifting devices by the above-mentioned Heinrich Schickhardt. Schickhardt, who served the dukes of Württemberg for decades as master builder and engineer,[32] in general does not appear as an ingenious inventor of new devices, but rather as somebody trying to provide the duchy with up-to-date technology that had already proven its efficacy elsewhere. In contrast to machine drawings in Leonardo da Vinci's manuscripts, composed roughly one hundred years earlier, Schickhardt's collection contains no theoretical reflections at all, whereas the relationship of his drawings to actual technical projects is extensively documented. Schickhardt's ability to employ all kinds of graphic techniques for drawing mechanical devices might have been above average. Nevertheless, it seems that his drawings represent an extraordinary case of preservation rather than an extraordinary way of using the medium. Thus they most likely testify to standardized practices in early modern engineering.

30 See Spies 1992.
31 See Leng (this volume).
32 See Schickhardt 1902, Popplow 1999, Bouvard 2000.

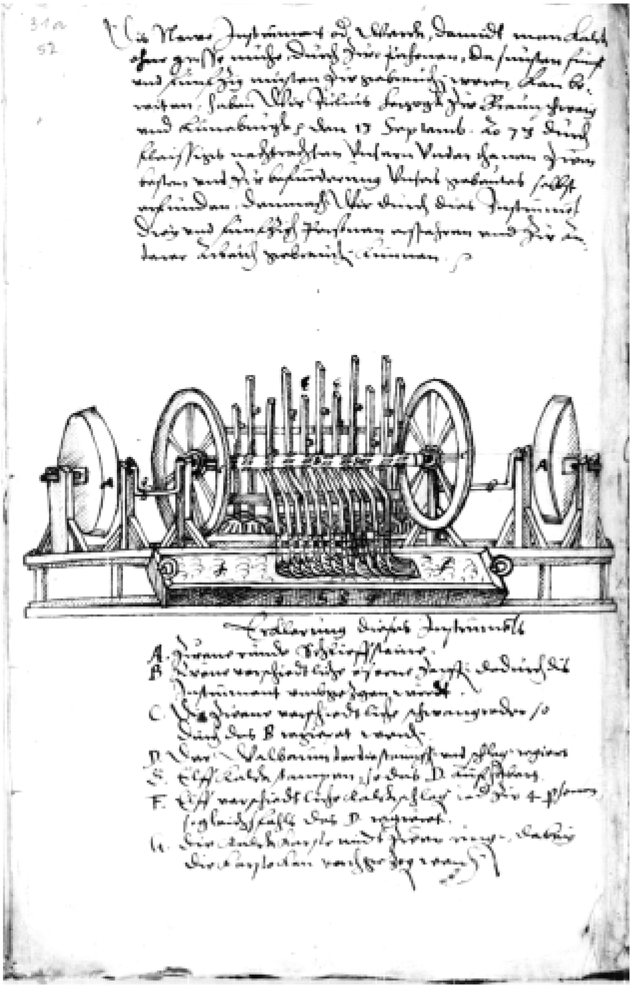


Figure 1.8. Presentational drawing of a device for stamping and mixing lime allegedly invented by Duke Julius of Brunswick-Wolfenbüttel, c. 1573. (Photo: Niedersächsisches Staatsarchiv Wolfenbüttel, Instrumentenbuch I, fol. 31^{r}.)

Around 1600, Heinrich Schickhardt supervised the building of several mills in Montbéliard, a project extensively documented in his papers.[33] One of the devices realized was a paper-mill. A survey drawing of this mill shows, in an idealized way, the most important parts of its inventory—two of the basins where soaked rags were reduced to pulp as the raw material for the production of paper have been carefully omitted to leave space to show such components as the mill's press (figure 1.9). At

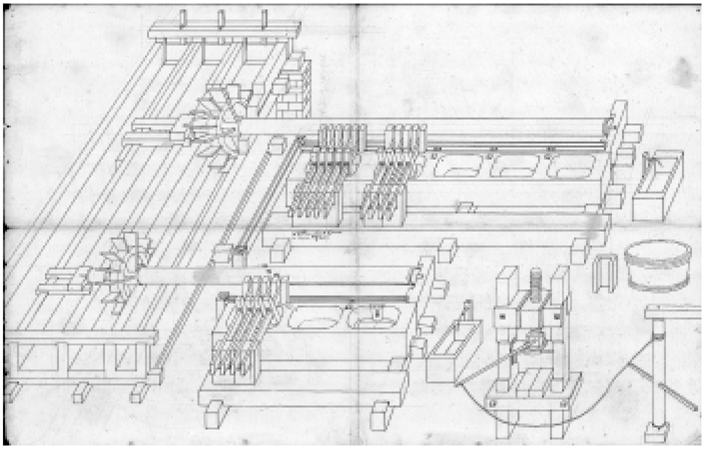


Figure 1.9. Inventory of a paper-mill in Montbéliard. Drawing by Heinrich Schickhardt, c. 1597. (Stuttgart, HStA, N220 T193, all rights reserved.)

which point of time the drawing was made is not definitively clear, but it is very likely that it was composed before the mill was actually built. A tiny comment written below the upper left basin says: "There shall only be four stamps in one hole" (instead of five as shown here). And indeed, the stamp at the extreme left is marked as obsolete by several diagonal lines. Most probably, a drawing like this was presented to the Duke of Württemberg for his formal approval or to keep him informed about such a costly project. Why the changes to details of the design were later documented in the way seen here remains unclear, however. Among several more detailed drawings of parts of this paper-mill is one showing a vertical section of one of the stamps, complete with measurements and, again, disclosing several corrected features (figure 1.10). Others concern the press, for example. Plans of the different storeys of the building have been preserved as well.

33 See Bouvard 2000, 63–77.

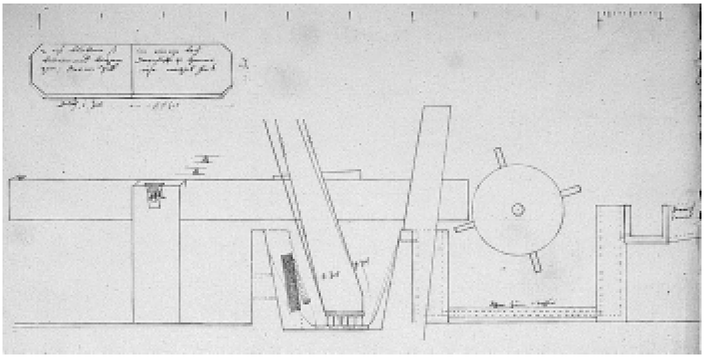


Figure 1.10. Vertical section of the cam-shaft and one of the stamps of a paper-mill in Montbéliard. Drawing by Heinrich Schickhardt, c. 1597. (Stuttgart, HStA, N220 T186, all rights reserved.)

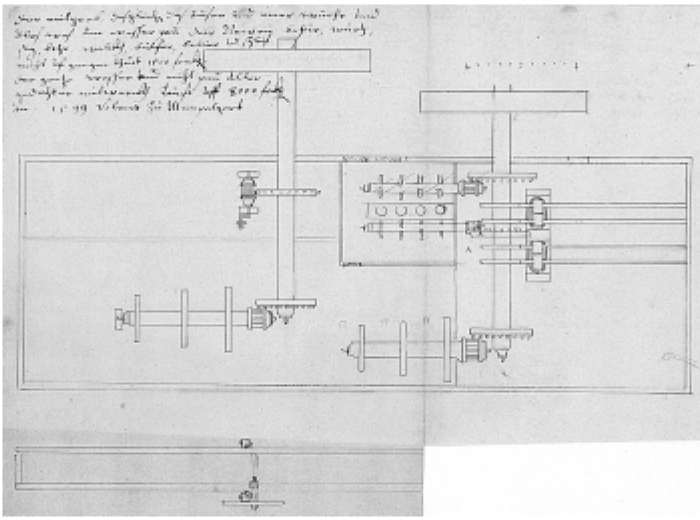


Figure 1.11. Ground plan of a fulling-/stamp-/grinding-/polishing-/drilling-/sawmill in Montbéliard, earlier version. Drawing by Heinrich Schickhardt, c. 1597. (Stuttgart, HStA, N220 T182, all rights reserved.)

Documents pertaining to another of the devices realized by Heinrich Schickhardt in Montbéliard document well the role of drawings in the relationship between engineer and artisan. In the course of constructing a combined fulling-/stamp-/grinding-/polishing-/drilling- and sawmill, Schickhardt again used different kinds of graphic representations, among them two ground plans. The first of these plans is a preliminary study of the disposition of the different mechanisms most probably rendered before the mill was actually built: A closer look reveals one set of stamps crossed out and a small note says that the water-wheels have to be set a greater distance from each other (figure 1.11). The latter addition shows that Schickhardt produced such plans to scale, and a roughly drawn scale is indeed to be found on the plan near the water-wheels. The second plan of the same mill shows that these changes had been carried out (figure 1.12).

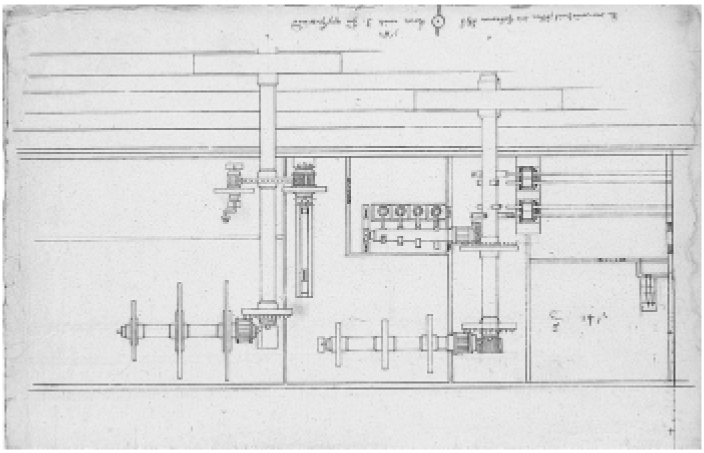


Figure 1.12. Ground plan of a fulling-/stamp-/grinding-/polishing-/drilling-/sawmill in Montbéliard, later version. Drawing by Heinrich Schickhardt, c. 1597. (Stuttgart, HStA, N220 T182, all rights reserved.)

The interesting thing about these two plans is that the second plan, at least, not only served to record what Schickhardt had planned, but was also part of the contract between Schickhardt and the carpenter who actually built the mill—as becomes clear from copies of documents preserved together with these drawings. Schickhardt, like most of his colleagues, was always engaged in several projects in different places at any given time. As he himself once wrote, he was in most cases responsible only for the design of a building or machine. He left plans and other information for the artisans to use, coming back weeks or months later to check on the realization of the project. In the case of the mill discussed here, Schickhardt composed a document on behalf of the Duke of Württemberg on 24 October, 1597, which specified how the mill was to be built by the carpenter. The text included the remark that “everything concerning the mechanisms and the rooms should be made properly and diligently according to the drawing.”[34] The drawing mentioned is the second plan, which indeed corresponds in detail to Schickhardt’s written description. At a later point in time, Schickhardt again noted the change of one detail, both on the plan and on the margin of the written document: The carpenter had provided the axle of the spice mill with three cams. This, however, resulted in the mill working “too fast.” Two cams, Schickhardt remarked, sufficed in this case. The importance thus placed on this detail is somewhat puzzling, however, because the document for the carpenter had mentioned only the gearing of the mills without specifying such details as the number of teeth on the toothed wheels. This is also true for other aspects of the project. The document laid down only the breadth and the width of the building; none of the other measurements were fixed in written form. This “openness” proves that drawings from the sixteenth century, even when they were used as plans to realize mechanical devices and thus at first glance resemble modern orthographic projections, still are not equivalent to modern blueprints. Furthermore, such drawings did not provide unambiguous instructions on the three-dimensional arrangement of the machine parts.[35] Even though Schickhardt provided the artisans with a wealth of information, a lot of “gaps” concerning the realization of certain machine elements remained to be filled in by oral instructions or through the expertise of the artisans. Finally, this example also documents the proximity of machine drawings to architectural drawings. As the realization of large mechanical devices also comprised the building in which they were housed, it can be assumed that drawings used in that process adhered to standards similar to that of plans used in the construction process of buildings, for example, larger residential houses. Such reciprocal dependencies of machine drawings and architectural drawings remain open to future investigation.

Figure 1.13. Documentation of the size of a leather disc for sealing pistons in a pump cylinder. Drawing by Heinrich Schickhardt, 1603. (Stuttgart, HStA, N220 T150, all rights reserved.)

34 “alles an mülwercken und gemecher dem abriß gemeß sauber und fleißig gemacht.” Stuttgart, HStA, N220 T182.
35 See Lefèvre 2003.

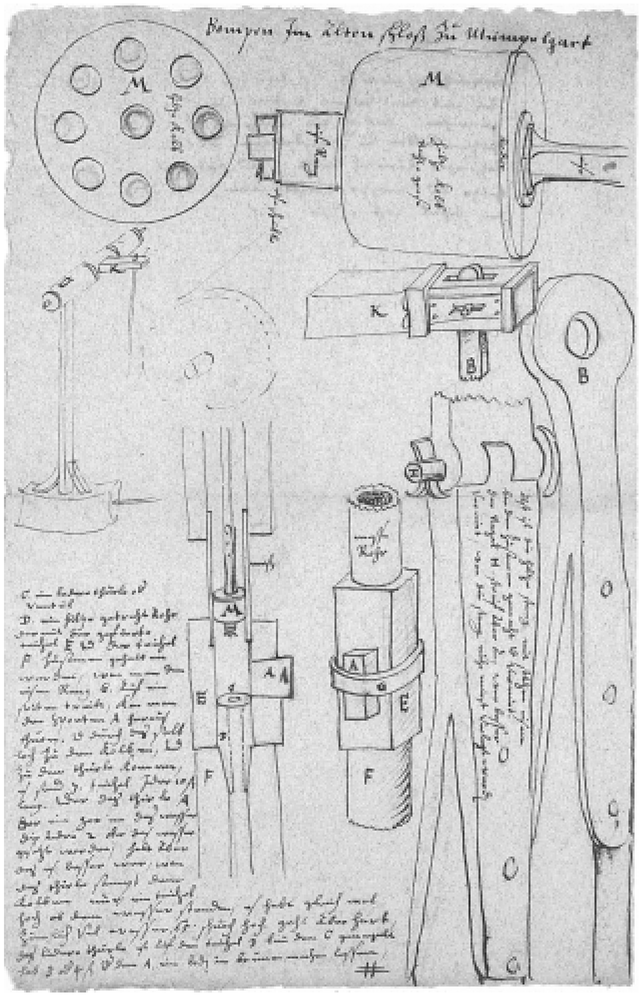


Figure 1.14. Inventory of parts of pumps for Montbéliard castle. Drawing by Heinrich Schickhardt, 1603. (Stuttgart, HStA, N220 T150, all rights reserved.)

A rarely documented and completely different type of drawing could play a minor role in the process of realizing mechanical devices: drawings determining the size of workpieces. Such dimensioning was, of course, a procedure that had long been required in any kind of building project and was solved by different means such as moulds and templates. Given its increasing availability in the sixteenth century, paper could be used for such a purpose as well. Such procedures seem especially likely in the production of the numerous toothed wheels for clockwork and automata. An example of this kind of drawing, again from Schickhardt's legacy, concerns a leather ring that served to seal up pistons moving up and down in pumping cylinders. This drawing with the remark "leather disc for the pumps"[36] (figure 1.13) probably was produced because the wear and tear of these discs frequently made their replacement necessary such that it was advisable to always have new discs at hand. Another drawing makes clearer the context of the employment of this disc: Here Schickhardt was concerned with restoring the pumps for the water supply of Montbéliard castle. The leather disc is to be found on the upper right part of the page, represented by the thin circle fixed to the right of the wooden piston marked "M" (figure 1.14). The function of this visual inventory of the parts of the pump is, again, not discernible.

3. MACHINE DRAWINGS AS ENGINEERS' PRIVATE ARCHIVES

Early modern engineers in many cases assembled personal archives with drawings of their own projects and drawings of devices realized by others. To be sure, the sorts of drawings discussed so far also could find their place in such collections. The following paragraphs, however, after briefly discussing drawings that served to illustrate engineers' own thought experiments and to document their own experiences with machines or machine elements in their workshop, will concentrate on different sets of drawings that helped engineers record the design of mechanical devices they saw during their travels.

As has been remarked above, it is still open to what extent Leonardo da Vinci's drawings of machine elements represented not only thought experiments, but arrangements of objects that had been tested in his workshop (figure 1.15).[37] In other engineers' documents known to date, hardly any drawings with these two functions can be discerned. This makes it extremely difficult to judge the role they might have played in the design practice of the fifteenth and sixteenth centuries in relation to three-dimensional arrangements or scaled-down models of machines. An early example of drawings that might be interpreted as thought experiments are a number of small studies of war ships in a manuscript by Mariano Taccola.[38]

Drawings produced by engineers while traveling are documented to a much greater extent than the thought experiments mentioned in the preceding paragraph. Parallel to artists' and architects' practices of keeping model books for reproducing

36 "lederne scheiblein zu den pompen." Stuttgart, HStA, N220 T150.
37 See Long (this volume).
38 See McGee (this volume).

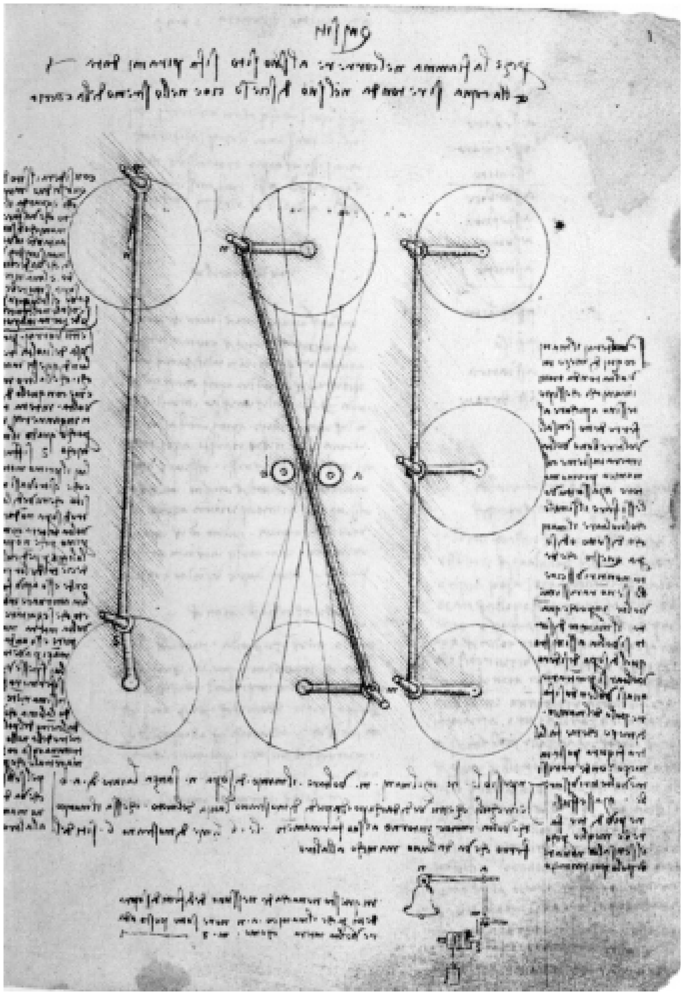


Figure 1.15. Arrangement of linkages to transfer circular motion. Drawing by Leonardo da Vinci. (Photo: Biblioteca Nacional Madrid, Codex Madrid, fol. 1r.)

different kinds of objects at some future point of time, a tradition reaching far back into the Middle Ages, engineers similarly assembled information on the variety of mechanical engines employed in early modern Europe. For the engineer, such drawings were an indispensable means of quickly recording information on devices seen elsewhere. Even if, for example, standard solutions for the design of flour-mills were widespread, there existed a multitude of designs for devices employing more complex gearing, as standardization in early modern mechanical engineering was by no means fostered institutionally. Engineers thus kept records of remarkable devices seen elsewhere, either in notebooks—usually, for practical reasons, of relatively small size—or on loose leaves.[39] In spite of their diversity, both north and south of the Alps such drawings seem to have followed some standard conventions with regard to the numerical and textual information conveyed. Measurements, gear ratios, and commentaries on the device's performance appear regularly, as either personally observed or orally communicated on the site. Especially with regard to this body of information, such drawings obviously adhered to conventions quite different from those which characterized presentational treatises.

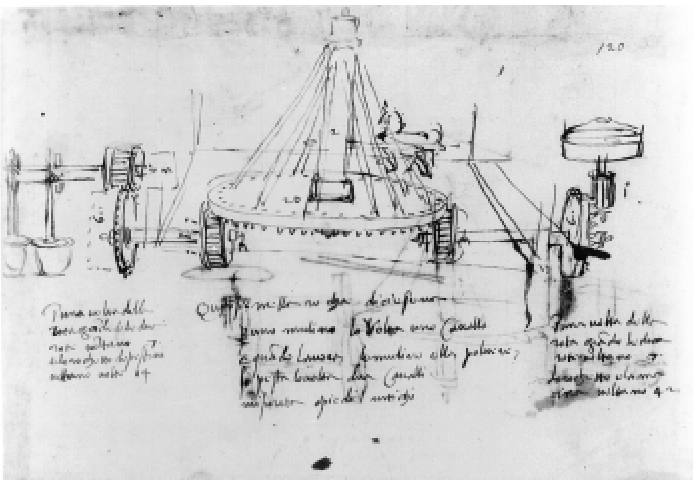


Figure 1.16. Sketch of a combined flour- and stamp-mill in Cesena. Drawing by Antonio da Sangallo the Younger. (Florence, Gabinetto Disegni e Stampe, U1442A^{r}.)

39 See, for example, the diary of two journeys to Italy by Heinrich Schickhardt, illustrated with numerous drawings of buildings and machines. Schickhardt 1902, 7–301.

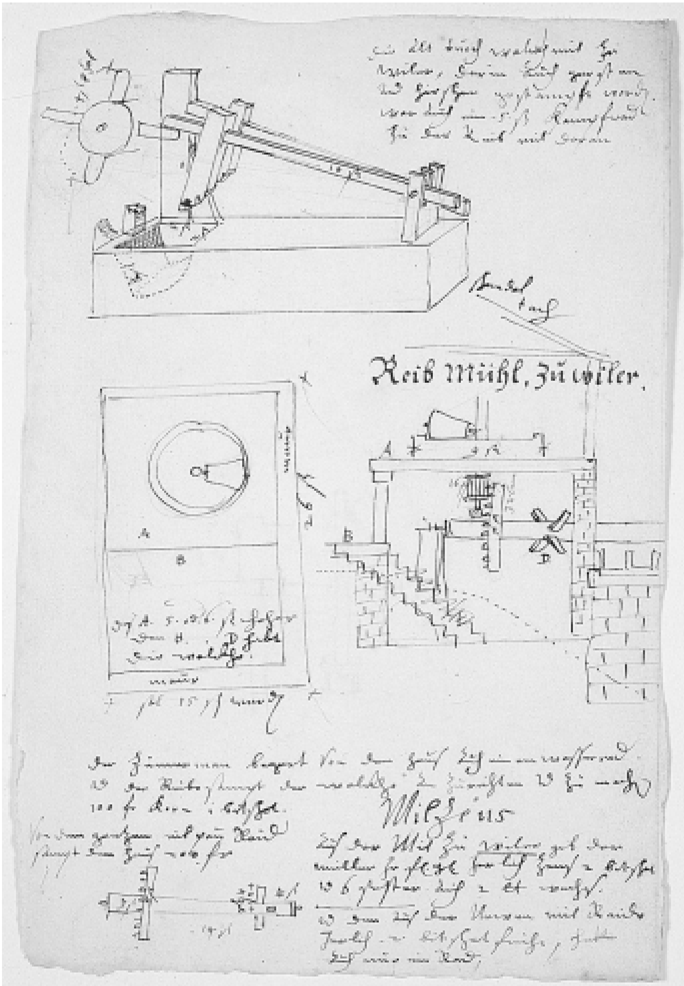
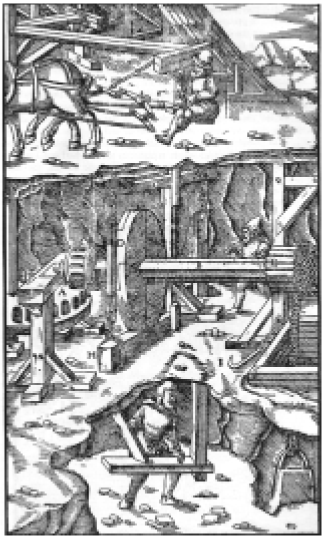


Figure 1.17. Sketches of a combined fulling- and grinding-mill at Wiler near Montbéliard. Drawing by Heinrich Schickhardt, c. 1610. (Stuttgart, HStA, N220 T241, all rights reserved.)

An early example of such drawings recording devices seen elsewhere is provided by Antonio da Sangallo the Younger in the first half of the sixteenth century. It shows a horse-driven combination of a flour- and a stamp-mill, which is said to have been located in Cesena (figure 1.16).[40] As was typical, the leaf includes information on measurements and gear ratios as they had been observed on the site. Similar examples from that period can also be found in the famous sketch-book of the Volpaia family from the 1520s.[41] Another example, one of numerous of such leaves included among the personal records of Heinrich Schickhardt, represents a combined fulling- and grinding-mill near Montbéliard.[42] This drawing exhibits an even greater density of information than the Sangallo example (figure 1.17). It furthermore testifies to the fact that, compared to the presentational treatises, engineers in such cases sometimes used a broader variety of graphic techniques to record what they had seen. Schickhardt, in this case as in many others, used not only perspective representations, but also vertical sections and top views. In each part of the drawing, he noted dimensions of the different parts of the machine and also wrote down the gear ratios of the machinery. The production of such drawings required a considerable sense of abstraction. Firstly, machines were housed in buildings, which, of course, were not transparent, so that it was actually impossible to see the machinery as it was portrayed by the drawing. Secondly, the point of view chosen for the representation of the machine—at a certain distance and slightly above ground level—is practically always constructed virtually, as it was hardly available to contemporary spectators.

How exactly engineers later made use of information recorded in this way is difficult to say. Of course, such drawings not only served individual purposes, but also provided a basis for communication with artisans, colleagues, and potential investors. In the case of Heinrich Schickhardt, the importance of such a collection is proven by the fact that he kept such leaves at home in a desk with drawers, each of which was reserved for one special kind of device.[43] In the sixteenth century, such archives of well-off engineers also usually included a collection of books—not necessarily on technical subjects only. Lists of books owned by engineers are documented, for example, for Leonardo da Vinci; again, Heinrich Schickhardt; and for the Italian engineer Giambattista Aleotti.[44] Towards the end of the sixteenth century, such personal libraries might also comprise printed machine books. At the same time, illustrations from printed books were also copied for private use. This is testified to by a loose leaf from the papers of Heinrich Schickhardt showing copies of machines employed in the German mining regions as they had been depicted in Georgius Agricola's *De re metallica* of 1556 (figure 1.18). The reason for the production of exactly these copies are unclear, as Schickhardt himself owned a copy of Agricola's book.

40 See Frommel 1994c, 418.
41 For this manuscript in general, see Brusa 1994, 657–658.
42 See Bouvard 2000, 60–63.
43 This can be deduced from a note in a document pertaining to the building of a mill in Pleidelsheim: "Mühlwehr wie das gemacht; ist beü den wasser gebeüen in der oberen Schubladen zuo finden." Stuttgart, HStA, N220 T212.
44 For Leonardo, see Leonardo 1974, II fol. 2^v–3^r and Leonardo 1987, 239–257; for Schickhardt, see Schickhardt 1902, 331–342; for Aleotti, see Fiocca 1995.



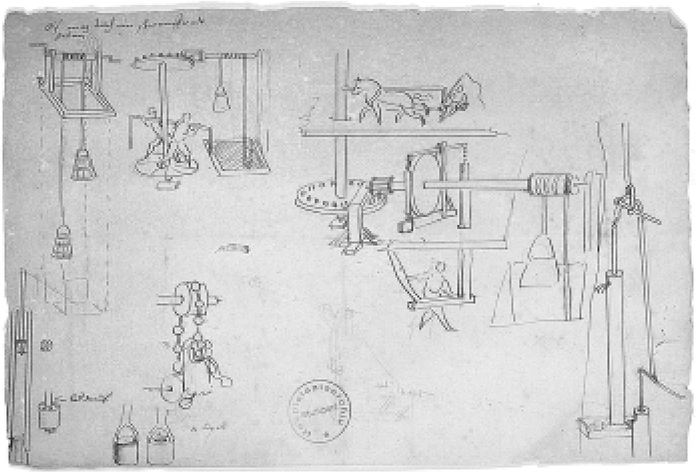


Figure 1.18. Top: Lifting device. Woodcut from Agricola 1556, 167. Bottom: Copies from Agricola's *De re metallica* by Heinrich Schickhardt, c. 1605. (Stuttgart, HStA, N220 T151, all rights reserved.)

Finally, another drawing from the legacy of Antonio da Sangallo the Younger might serve to illustrate the difficulties of unambiguously assigning early modern machine drawings to the three contexts of representation, realization, and documentation discussed so far. The leaf shows different views of a pump (figure 1.19).[45] As the brief explications make clear, its peculiarity was that the valves usually employed in pumps had been replaced by metal balls. From this innovative feature it could be assumed that the leaf represented a study that was not connected to a particular project. From the information given on the numbers of teeth of the toothed wheels, it could also be assumed that the drawing shows a device that was actually in use. Even if this was indeed the case, it would still remain unclear whether the device had been designed by Antonio da Sangallo or whether it represented a device made by others, which had been investigated during his travels. Ultimately, it remains open which purpose such a documentation actually served. The analysis of early modern machine drawings is often confronted with such problems of interpretation. To narrow down the possibilities of interpretation, descriptive texts, text fragments on the drawing and textual documents preserved with the drawings again and again prove most useful. Where such additional material is missing—which is often the case due to the frequent separation of pictorial and textual sources practised in a number of European archives some decades ago—interpretation is often confronted with considerable difficulties.

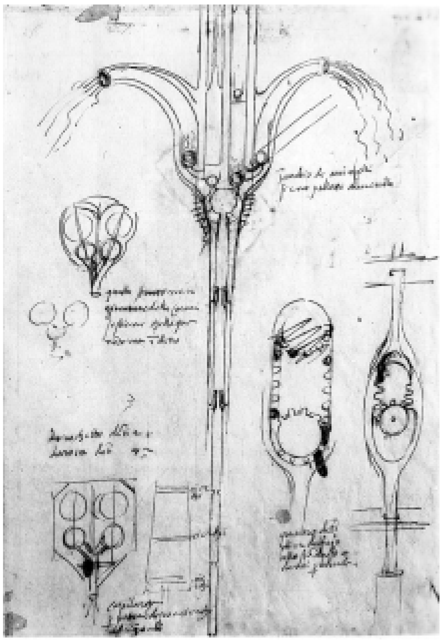


Figure 1.19. Studies of pumps with the usual valves replaced by metal balls. Drawing by Antonio da Sangallo the Younger. (Florence, Gabinetto Disegni e Stampe, U847A^{r}.)

45 See Frommel 1994c, 335.

4. DRAWINGS SERVING THEORETICAL CONSIDERATIONS OF MACHINES

This fourth category of machine drawings represents a special case in the classification proposed here. Up to this point, machine drawings have been classified according to the social context of their employment: presentation to a broader public, realization of concrete projects, storing information for the engineer's own use. The theoretical analysis of machines by means of drawings appears to be orthogonal to these categories, as such an approach might be found in each of these three categories. To be sure, the definition of "theoretical" in the context of early modern engineering drawings is still an open question. In general, the sixteenth-century theory of mechanics is understood as consisting in the analysis of the simple machines based on the lever and the balance. However, there also are engineering drawings that testify to general reasoning on machines without any reference to preclassical mechanics and its visual language of geometrical diagrams. Drawings of standardized types of mills in a treatise by Francesco di Giorgio Martini could be adduced as an early example,[46] a drawing by Antonio da Sangallo that will be discussed below as a later one. Engineers' considerations of working principles of machines in drawings like these might be labelled "theoretical" as well, but the establishment of corresponding definitions lies beyond the scope of the present contribution. The following paragraphs thus mainly concern the appearance of the visual language of preclassical mechanics in sixteenth-century engineering drawings.

In the sixteenth century, mechanics gradually emerged as an independent discipline. This process was inseparably connected to the reception of ancient sources. Pseudo-Aristotle's "Mechanical Problems" were now edited and commented upon as well as the works of Archimedes, Hero of Alexandria and later those of the Alexandrine mathematician Pappus. Additional sources comprised medieval treatises in the tradition of the *scientia de ponderibus,* most prominently those of Jordanus Nemorarius. All of these approaches were founded on the theoretical analysis of the balance with unequal arms and the lever by means of geometrical proofs. This common basis facilitated attempts in the sixteenth century to unify all of these different strains from the Greek and Hellenistic eras and the Arab and European Middle Ages. In this context, special attention was devoted to the classification of the five simple machines (lever, wedge, winch, screw, and pulley) dating back to Hero of Alexandria, which, for example, guided Guidobaldo del Monte in structuring his influential "Mechanicorum liber" (1577). As early as the late fifteenth century, as soon as the work on "rediscovered" texts on mechanics began, engineers strove to use this body of theory to investigate more closely the properties of the sixteenth-century machinery with which they were dealing. As the analysis of the simple machines proceeded by means of geometrical proofs to determine relationships of distance, force, weight and velocity, graphical representations played an important role. The corresponding visual language is documented, for example, in the illustrations of Guidobaldo del Monte's treatise and was presented concisely on the title page of the German translation of

46 See Long (this volume).

Figure 1.20. Geometrical analysis of the simple machines as the foundation of mechanics, and their practical application. Frontispiece of Daniel Mögling's *Mechanischer Kunst-Kammer Erster Theil* (Frankfurt 1629).

Guidobaldo’s work in 1629 (figure 1.20). The frontispiece presented an overview of the simple machines and their geometrical analysis, alluding to their practical application as well.

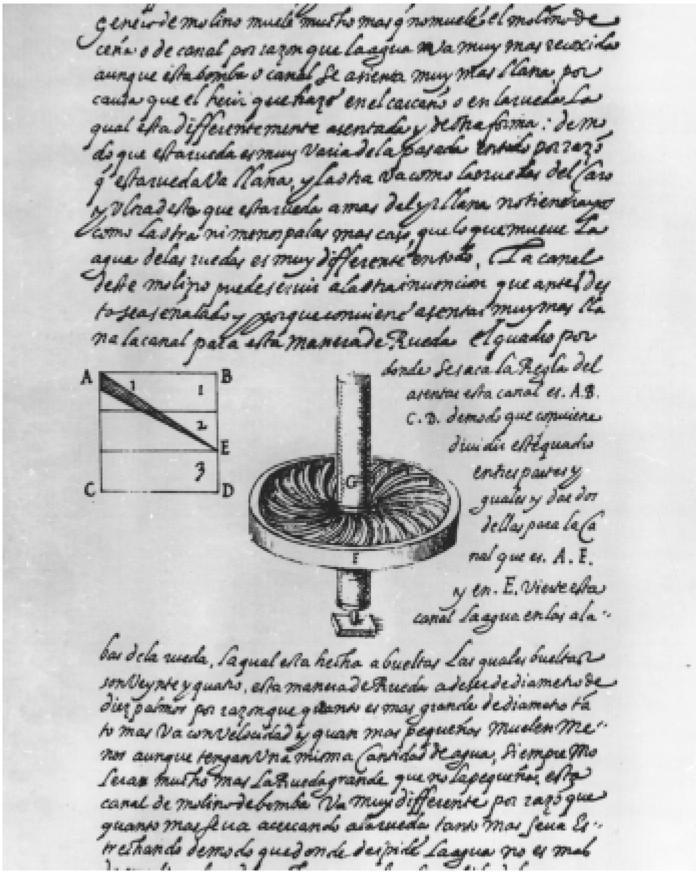


Figure 1.21. Diagram to determine the inclination of a conduit to drive a horizontal water-wheel. (Photo: Biblioteca Nacional Madrid, Los veintiún libros …, Mss. 3372–3376, fol. 290r.)

The few examples known to date that combined engineering drawings with geometrical analysis in terms of the simple machines are found in engineering treatises, in which they aimed to underline the author's acquaintance with the foundations of contemporary science. The author of the Spanish engineering treatise "Twenty-one books of engineering and machines" in the 1570s thus analysed the inclination of conduits to drive a water-wheel by means of a geometrical diagram (figure 1.21).[47] Giuseppe Ceredi, physician to the Dukes of Parma and Piacenza, in a treatise published in 1567 concerning the application of the Archimedean screw to irrigation, also dealt extensively with the theory of the balance and the lever as the theoretical foundation of the analysis of machines.[48] Arguing for the superiority of the kind of crank he had chosen to drive his Archimedean screws by manpower, Ceredi also incorporated geometrical abstractions in the illustration of his own solution in order to allude to the scientific reasoning underlying his choice (figure 1.22).

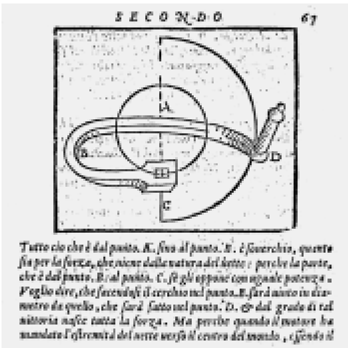


Figure 1.22. Geometrical analysis in terms of the lever of a crank to drive an Archimedean screw. (Ceredi 1567, 67.)

A similar kind of explanation was later given by Simon Stevin in his treatise "De Weeghdaet" with reference to a typical crane operated by a tread-wheel employed on early modern riversides.[49] In private documents of sixteenth-century engineers, the employment of drawings for theoretical reflections is documented more extensively only in Leonardo da Vinci's notebooks. His analysis of such factors as friction and the strength of materials, in particular, still appears to have been singular. In sixteenth-century manuscript material, no comparable theoretical analysis of machine elements is known. In the process of realizing early modern machines, such theoretical analyses seemed hardly to play a role. An exception, which, however, again concerns a preliminary stage of evaluating the design of a machine, was later reported by Galileo Galilei. While Galileo was at the Florentine court, a foreign engineer who remained anonymous presented the Duke of Tuscany with a model of a geared mechanism allegedly suitable for employment in different kinds of mechanical devices.[50] The crucial fact about the engineer's proposal was that his device entailed a pendulum, which, the engineer claimed, greatly increased its performance. In an undated letter sent to the engineer, Galileo Galilei, who had been present at the demonstration, sub-

47 See Turriano 1996, fol. 290r.
48 See Ceredi 1567.
49 See Stevin 1955, 344.
50 See Galilei 1968b.

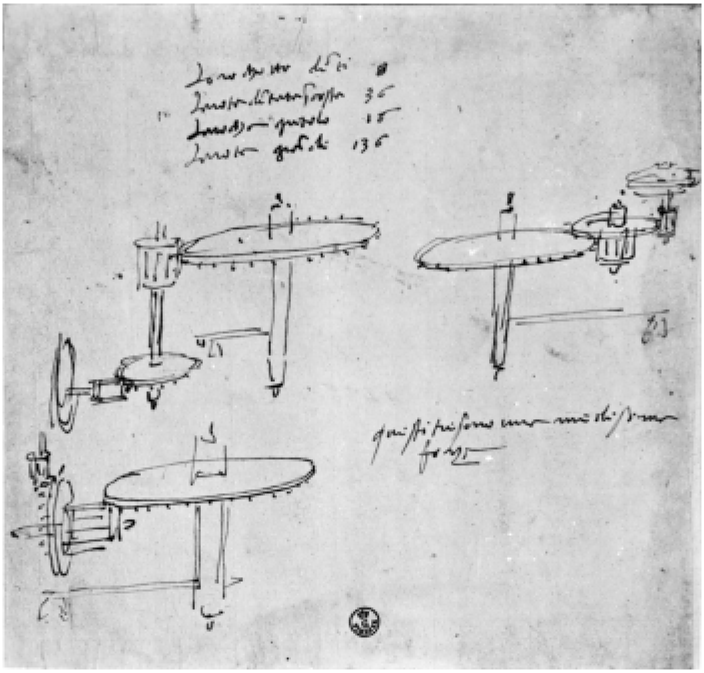


Figure 1.23. Study on different combinations of the same gears for a horse-driven flour-mill. Drawing by Antonio da Sangallo the Younger. (Florence, Gabinetto Disegni e Stampe, U1487A^{r}.)

stantiated to the engineer why he considered this hope to be unfounded. In part of this letter, Galileo reduced the major features of the model presented to a geometric drawing in order to enable its study according to the principles of the balance. The original drawing, however, has not been preserved. This example shows that such theoretical analyses in the context of discussing the design of particular machines can be expected above all in court contexts. In this framework, the “scientific” foundation of personal judgements gained increasing importance over the course of the sixteenth century.

In engineers’ personal accounts, it was primarily measurements and gear ratios that were reported extensively. However, it does not seem that they generally used this information as a starting point for further reasoning of a more general nature. The only drawing known so far that points in such a direction is, again, part of the collection of Antonio da Sangallo the Younger. It shows ways to combine identical gearing assembled differently in space, stating that they are all "of the same power"[51] (figure 1.23). This comment shows that in early modern engineering practice, concepts like "force" or "velocity" were used by engineers to describe the performance of such devices as a matter of course, without referring to the contemporary scientific definitions of these terms. Even if theoretical reasoning in mechanics did not emerge directly from the use of such prescientific concepts, it seems obvious that the intensified dissemination of preclassical mechanics towards the end of the sixteenth century, at least in Italy, sharpened the perception of the gaps between the scientific and the colloquial use of such terms and thus further stimulated reasoning among figures familiar with both cultures. Such gaps also became obvious with regard to the different visual grammars of engineering drawings and geometrical diagrams of preclassical mechanics, which in the end concerned similar objects, namely basic machine elements. The merging of such different traditions of knowledge raised fruitful challenges for the theoretical investigations in mechanics pursued, for example, by Guidobaldo del Monte and Galileo Galilei.

CONCLUSION

The preceding investigations have shown that early modern machine drawings are not only relevant for the reconstruction of the state of the art of contemporary machine technology. Although an epistemic history of early modern engineering still remains to be written, the analysis of the drawings technical experts produced testifies to the fact that their knowledge far exceeded the *tacit knowledge* of the artisan: Machine drawings turn out to have been the product of a highly differentiated form of knowledge that could take on a number of functions in different contexts of employment. This is especially evident with regard to the drawings discussed here, which were, for the most part, closely related to engineering practice. Such drawings open up new possibilities of contextualizing Leonardo da Vinci's drawings as well as those of the more representative machine books.

51 "[…] sono una medesima forza." Frommel 1994c, 448.