Mega-Structures of the Middle Ages: The Construction of Religious Buildings in Europe and Asia, c.1000-1500

Maarten Prak

Utrecht University

maarten.prak@let.uu.nl

Abstract:
How did medieval builders manage to construct Gothic cathedrals—buildings which are still among the tallest structures in the world—without access to the modern engineering theories? The paper investigates medieval building knowledge and the way it was transferred across the generations. Printed information only seems to have emerged in the course of the 15th century. Construction drawings were limited to details. By implication, the relevant knowledge must have been transferred on a personal basis. Its underlying principles therefore must have been reasonably simple. The paper attempts to demonstrate that a modular design and execution was underpinning much of the construction work on large projects such as European cathedrals. By briefly considering building projects in the Middle East and Asia, it also suggests that this was probably true throughout Eurasia.

Introduction

In the medieval Latin West[1], building must have been among the most important industries, constituting perhaps as much as five percent of the economy. Between 1136—when building started on the new choir for the church of Saint Denis, north of Paris, presumably the first Gothic project—and the middle of the fourteenth century, medieval Europe was in the grip of what amounted to a building boom. Major projects continued to be undertaken in the following centuries. The products of this boom still amaze observers today. In many European towns the cathedral and other medieval churches are among the main tourist sights and keep attracting crowds of visitors who travel long distances to admire them. Even today, the cathedrals are among the tallest structures in many a European town.

The Latin West was not the only one area of Eurasia where major building projects were undertaken for religious purposes. At roughly the same time, i.e. during the 11th-13th centuries, perhaps as many as 5,000 temples were constructed in the plain of Pagan in what is now northern Burma (Mayanmar). In China, during the Song (960-1279) many pagodas and pagoda towers were built, of heights not previously attained. Meanwhile, in Byzantine Asia Minor more routine church construction continued apace. In all of these areas builders used the same raw material to construct their buildings: brick. Obviously, brick was not used exclusively; many of the famous medieval cathedrals of Europe are constructed in stone. But as we will see, brick was used in areas where stone was not available on site. The use of identical raw materials adds another element to the comparability of the structures under discussion in this paper. In other words, the building industry provides us with a laboratory-type of opportunity to compare the application of cutting-edge technology under more or less identical circumstances across Eurasia.

What interests us here more particularly is the knowledge available to the people responsible for executing projects that required this cutting-edge technology, and how such knowledge was transferred from one generation to the next. Unfortunately, medieval builders have left preciously few written documents about the theories underpinning their work. We will, of

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[1] This term is used because later on we will discuss building in the Byzantine Empire, which is also located in Europe. To avoid the cumbersome description, however, I will use the word "Europe" when in fact I mean the Latin West.

course, utilise those documents articulating construction theories, but will also have to rely to an important extent on the material record, i.e. the church buildings themselves, and what these can tell us about the ways in which they were constructed.[2] As concerns building knowledge, I have found the distinction between propositional and tacit knowledge particularly useful. Propositional knowledge is factual as well as theoretical, logical and explicit, and can therefore be learned from printed sources. Tacit knowledge, on the other hand, is implicit, non-linear, and addresses "how" rather than "why" questions.[3] Perhaps I should underline that this division between propositional and tacit knowledge is not identical with Mokyr's (2002: 4-5) distinction between propositional and prescriptive knowledge, which he equates with science and technology. This paper is concerned with technology that can be disaggregated into propositional and tacit components (Epstein&Prak: 5-7).

The paper is also implicitly predicated on the assumption that works of art are not the product of a single individual genius, but rather of a collaborative process involving a great many contributions, which have to be coordinated (Becker 1984). Due to the collective nature of works of art—and this is, of course, quite obviously true for architectural works—the results are hardly ever completely identical, but instead tend to vary. It is the argument of this paper that specific combinations of a modular understanding of building constructions and the modular execution of these constructions, helps explain how builders in the pre-modern era were capable of creating very complex projects, the mechanics of which the builders themselves were incapable of understanding theoretically.

[2] This approach has been inspired especially by the works of John James and Robert Mark; see titles listed in the bibliography.
[3] Equivalent terms are `explicit' and `implicit knowledge', or `overt' and `covert knowledge': Reber 1981: 10, 15.

I. Europe

1. Church building

Between roughly 1000 and 1500 impressive numbers of impressive buildings were created in Europe. In Cologne, in Germany, at the time a city of perhaps 25,000 inhabitants, no fewer than 28 churches and chapels were built between 1150 and 1250. Its huge cathedral, which was started in 1248, and only finished in the nineteenth century, is not even included in that figure. The French town of Chartres, with a mere 8,000 inhabitants, commissioned a cathedral that is still one of the highlights of the Gothic movement in architecture. The tower of Strasbourg cathedral was, with its 142 metres, the tallest structure in France before the Eiffel Tower was built in 1889, and in fact in the world for quite a long time. St. Mary in Gdansk in Poland, built between 1343 and 1496, is said to be the tallest building in brick in the world. These facts impress because of the great expenses laid out by often relatively small communities, implying issues of economics, but also because of the engineering accomplishment of their builders.

The industry was, moreover, remarkably innovative. Between roughly 1150 and 1250 the new Gothic style transformed both the outlook and the construction of religious buildings in fundamental ways. The stylistic innovations were first and foremost a radical shift in the balance between walls and windows. Romanesque buildings had thick walls and relatively few windows, whereas Gothic churches seem to consist almost entirely of glass, held together by relatively slim stone pillars. And this is only the most obvious of a whole series of stylistic innovations introduced in European church building since the twelfth century. Other such innovations include the placing of towers, which were multiplied by Gothic architects, the development of sculpted porches placed in deep recesses, and the creation of round, so-called rose windows (Wilson 2000: 69-70). The Gothic design was first developed in the region around Paris, and many of the innovations also originated there, although not necessarily always in connection to the famous cathedrals, as smaller churches could be likewise sites of experiments (James 1989: ch. 9). From the Île-de-France it spread to various other parts of Europe, probably first to the British Isles, because of the close political and hence cultural contacts between the two countries. The Gothic style was, however, adapted in each of these regions to local tastes and traditions. In England, for instance, flying buttresses were rarely found, because builders continued to construct thicker walls as they were used to doing

(Wilson 2000: 74). In Northern Germany, where natural stone was in short supply, builders had to create Gothic designs in brick, creating in the process the distinctive *Backsteingotik* (or `brick Gothic') that we will discuss in more detail later (Böker 1988).

Construction challenges for tall buildings include the problems created by the structure's own weight, the resistance to pressures from the natural elements, especially wind, and the necessity to use natural light to illuminate the interior of the building (Mark 1990: ch. 2). Gothic design was a huge improvement over its predecessor (Romanesque) in the latter area, because it allowed far larger surfaces of glass. At the same time, the height of the buildings made them more susceptible to wind pressures. The necessarily less solid construction of the vertical elements only increased that problem. Builders had to find solutions to overcome these problems.[4]

One important help was the "invention" (Gimpel 1977: 121) of the flying buttress. Through a complex combination of horizontal extension and vertical loading, builders managed to prevent the vaults from pushing the walls of the church outwards (Borg&Mark 1973; Wolfe&Mark 1974; Clark&Mark 1984; Mark 1990: ch. 1, 108-22). Another was the development of the pointed arch, which through the double arc of its construction creates more downward rather than outward pressure (Mark 1990: 107-08). Builders had to intuitively understand these problems, and find solutions for them, as they had no laboratories to test the various pressures to which their constructions were exposed (cf. Coldstream 1991: 60).[5] The answer is, that they were probably simply finding out during the building process itself. The building process was conducted as a series of on-site experiments, in which the builders' experience from previous projects was tested against novel challenges.

The percentage contribution of the building industry to the economy as a whole cannot be established with any precision, but it must have been substantial (Pounds 1974: 334-36). Later figures suggest that in the order of five percent of the urban workforce were builders, and perhaps as much as 10-15 percent of industrial workforce was employed in the building industry.[6] Obviously, not all of this was spent on churches. On the other hand, Gothic church building produced substantial spin-offs, for instance in glazing, but also for interior decorators, such as painters and embroiderers. Medieval stone work was covered in paint,

[4] Ball 2008: ch. 8 provides a particularly helpful survey of Gothic construction techniques.
[5] For modern laboratory experiments on Gothic constructions, see the works of Robert Mark, esp. (1990).
[6] These figures are substantiated in an as yet unpublished paper on the building industry of Holland, 1500-1815.

gone in most Protestant countries, but still visible in Southern European churches. Dozens of altars were, moreover, decorated with paintings, commissioned by guilds, confraternities, or private donors. Works like the Ghent altarpiece by the Van Eyck brothers, created in the 1430s for a private altar in the St.Bavo church, provide a hint of the spectacular, and by implication labour-intensive character of the late medieval painting industry.

Cathedral building was financed from a variety of sources, also depending on the particular context. Thus, Notre-Dame in Paris was patronised to an important extent by the French royal dynasty and the great families of the capital, who also had a stake in religious offices in the French Catholic Church (Kraus 1979: ch. 1). On the other hand, Our Lady in Antwerp, begun in 1352 and destined to become the largest Gothic church in the Low Countries, was mainly financed with the help of private donations from local citizens and foreign merchants active in Antwerp. Bequests alone constituted between 15 and 32 percent of annual income for the church. On top of that, the church profited from Antwerp's booming business. Located in the centre of town, it could levy dues on business activities taking place on church land. In 1431 rents on business premises located within the church immunity amounted to less than ten percent of total income from property assets, by 1565 this had increased to 85 percent, providing the church with substantial additional funds (Vroom1983: 66-67, 75-76).

All of this goes to show that the building of great churches in Europe during the Middle Ages was a major activity, both in terms of the numbers of people and the amount of money involved in the construction itself but also in the adjacent industries, as well as in terms of the technological challenges that the builders and their patrons set themselves. By implication this should turn our attention to the workforce, and subsequently to its training.

2. The workforce

Major building projects employed wildly fluctuating workforces. During the summer months of 1253, up to 435 people were working on Westminster Abbey, of whom 130 stone masons and 220 assistants employed on various tasks. In September the number was halved, mainly because the assistants left the site, presumably to participate in the harvest. For the Gothic choir of Aachen Cathedral, which was constructed between 1355 and 1414, the accounts show how in the second half of 1400 the workers concentrated on the construction of several windows. The number of employees involved in this work was between 9 and 11. For the building of the cathedral in Regensburg, master Conrad Roriczer employed in 1459 between eight and twelve stone masons and a lodge-assistant, an apprentice for three weeks, as well as two to four carpenters. During most of the fifteenth century the builders of St. Stephen's Cathedral in Vienna employed 7-10, sometimes 11-13, and in 1476 14-21 journeymen, but at times a mere 2-3 (Binding 1993: 272-76). The employment of one, or at most a couple dozen workers seems to have been the normal situation. These "routine" activities could be interspersed with short, sharp campaigns when much larger numbers were employed.

The accounts of the building of St. Lorenz in Regensburg between September 1445 and September 1446 give us an idea of the various types of workers. The Master, who was on site full-time, oversaw the work of seven stone masons in the lodge, one lodge-assistant, 5-6 workers in the quarry, three workers "in the wheel" (i.e. the crane used to lift stones), one in the chalk lodge where the mortar was prepared, and at times a carpenter. A carpenter and a black smith were also permanently employed at the quarry. For the building of Chartres Cathedral, 12 stone masons were employed during much of the fourteenth century, 104 stone layers, 7 assistant stone layers, as well as 8 mortar makers and 36 plasterers (ibid.: 276-77). We thus see a combination of skilled, semi- and unskilled labour combining their efforts on the building site.

The specialist workforce was recruited from a wide area and was, by implication, highly mobile. On the building site of Prague Cathedral we find in 1372-78, next to the local workers, Germans from Regenburg, Glatz, Cologne, Würzburg, Andernach, Brünn, Nurnberg, Frankfurt, Strasbourg, Mainz, Braunschweig, Rothenburg, Dresden, Freiburg, Saxony, Schwaben, Prussia, Westphalia, from Linz and Vienna, as well as workers originating from Brabant, from Hungary and from Poland. Of 131 stone masons employed at Vale Royal Abbey between 1278 and 1280 only ten percent at most were locally recruited; the rest came from a variety of English counties. On the other hand, at least half the carpenters and black-smiths were local people, and of the assistants—presumably half- or unskilled—around ninety percent came from the area itself (ibid.: 284-85).

The mobility of the stone masons is confirmed in the employment strategies of the town of Kampen, in the northern Netherlands. During the fifteenth and sixteenth centuries the town's stone masons, mainly charged with supervising the building of the town's major churches, came from Xanten and Venlo, from Delft and particularly from Coesfeldt in Westphalia. Their workers too were mostly from out-of-town, especially from the areas where stone was found, like Westphalia, or where major building projects were underway, such as

Utrecht and ‘s-Hertogenbosch which were both building important cathedrals (Kolman 1993: ch. 7, and 193). The town’s official carpenters, on the other hand, seem to have been recruited mostly—although not exclusively—from the ranks of local masters (ibid.: ch. 9).

Stone masons

Transportation costs were such, that stone was preferably quarried on the site of the building project. Stone used in Marlborough in 1237 cost 3 shilling per unit at the quarry, but another 22 shillings for carriage. In the early fourteenth century, land transport of stone across five or six miles cost the equivalent of the stone itself. It was obviously cheaper to carry it across water. Stone from Normandy was shipped through Caen to England, and in 1287 the transport costs of a shipload ordered for the building of Norwich Cathedral was only twice as expensive as the stone itself (Salzman 1967: 119, 132-33). Nonetheless, the costs of transport were potentially taking up such a huge part of the project’s budget, that there were major benefits in building with stone quarried on the spot. Much of Paris, for example, is built on top of underground quarries which are reckoned to total 200 miles of tunnels; compare that to the 130 miles covered by the Paris Métro system (Gimpel 1977: 60). France was especially fortunate with its endowments of stone suitable for building. The northern Netherlands, on the other hand, were completely dependent on quarries south of Brussels, or Germany, and stone inevitably had to be carried over substantial distances. This had two major implications.

The first implication was that stone was preferably prepared at the quarry, rather than at the building site, whenever the two were situated far apart. Otherwise, expensive transport would be wasted on excess material. Moreover, this allowed the identification of low-quality pieces before shipping (Janse&de Vries 1991: 10). In the Low Countries, stone was found in a crescent-shaped region running roughly from Ghent, across Brussels, to Maastricht. This stone supplied also the northern territories which were deprived of their own stock of raw materials. The rivers Meuse and Scheldt served as the main arteries for shipping (ibid.: 10-19). The system eventually became so sophisticated, that in the course of the Middle Ages, complete pre-fab churches would be prepared at the quarry, to be shipped as parts to the building site, where they were assembled by local workmen (Meischke 1988: 79-84; Hurx 2007).

The other implication was that crucial knowledge tended to be connected to the building material. Again the Low Countries provide us with several intriguing examples (Janse&de Vries 1991: ch. 5). Between the late fourteenth and mid-sixteenth century, successive generations from the Keldermans family—who originated from Brussels but later moved to Antwerp—were contracted to design and help execute numerous public buildings, religious as well as civic, in the Northern Netherlands. They were commissioned to design complete plans ("pattern" in the sources), as well as specific features, and provided the templates for the various stone parts necessary to erect the structure. The Keldermans firm supplied their customers with sculptures (Mosselveld ed. 1987: ch. 1). The point here is, however, that they combined their work as designers and sculptors with that of stone supplier. Accounts of public works from 1458 (Brussels), 1493 (Brussels), 1494 (Alkmaar), 1497-1503 (Utrecht) show the family in this latter capacity. At other times the stones were delivered by other suppliers who executed the designs made by the Keldermans firm (Janse 1991: 173).

Carpenters

Before the cathedral was built in stone, it had to be constructed in wood. Because these wooden structures were taken down after the building was finished, we tend to overlook the contribution of the carpenters in the building process. It was, however, vital to the whole process. In the first place, carpenters built the scaffolding that allowed the builders to move around. For the building of Westminster cathedral the accounts of 1324 refer to 400 pieces of alder of 38 feet, 25 pieces of 20 feet, and 61 pieces of ash of 42 feet; all this wood was used for scaffolding. In 1532 the "skaffolde powles" at Westminster included 24 pieces of alder and 70 pieces of ash. In Exeter the builders used, in 1325, 15 great poplars and 100 alders. The wooden poles would usually be tied together with ropes made of bast (Salzman 1967: 318-19). The carpenters erecting the scaffolding for Regensburg Cathedral received a supplement on their wages for the dangers related to the heights of their work (Binding 1993: 319).

Secondly, and even more important perhaps, all the complex parts were set in wooden frames until the mortar hardened. Stone vaults, for instance, were built entirely on wooden support structures, which had to be left in place to allow the stone and the mortar to settle, a process that could take up to six months (James 1982: 41). Thirdly, some important parts of the church were built of wood, most notably the roofs. These were covered in stone, but underneath they consisted of wooden frames and boarding. It is estimated that the roof of Our Lady's Church (*Liebfraukirche*) in Ingolstadt, Germany contains the wood of 3,800 trees—just to give an idea of the amount of woodwork involved (Schock-Werner 1978b: 58).

Unfortunately, very little is known about the carpenters who undertook this work. Art historical research has concentrated overwhelmingly on the stone masons. We do know how carpenters had to be able to use a variety of tools to exercise their trade. The largest number of different items listed in a study of medieval building tools is related to carpenting. These include various types of axes, saws, drills, hammers, and chisels, as well as compass, square, plane, file, and rasp (Van Tygem 1966: 1-70). Carpenters seem to have been mostly local craftsmen, but this one must infer from the absence of references to itinerant carpenters rather than from any positive evidence.

In places where the quarry and the building site were in close proximity, the technical knowledge was also clustered, but where these two were located at a distance from each other, the labour force had to be mobile to ensure a sufficient exchange of vital knowledge. This mobility of labour was further stimulated by the fact that the building process itself consisted of short, intensive campaigns, interspersed with periods of slow progress, when local craftsmen may have been dominant on the site. Both the organisation of the building process and the distribution of technical knowledge required a collaboration of local and itinerant craftsmen.

3. Knowledge

In 1516 Lorenz Lechler, a German mason from the Neckar area, set down in writing a number of "Instructions" on the building trade for his son. The timing of this written document is in itself significant, because there are very few similar documents from an earlier date; we will have to come back to this in the next section. Here, however, we are interested in its contents. Even though he did not set this out in quite such a systematic way, one can distil from the Instructions four major problems facing the builder, once the decision to launch a major project had been taken (Shelby&Mark 1979: 115). First he had to make sure he obtained the right quality of stone. We have already discussed in the previous section how vertical integration of the industry covered this problem. Second, a decision was required about the scale of the building, and the type of measurements to be used. Lechler distinguished between the larger Old Foot, which was bigger, and the more recently fashionable New Foot, which allowed more subtle features. Third, the builder had to use his accumulated knowledge to overcome pressing problems that would arise during the building process. At several points Lechler emphasised that a builder could not rely on the rules and principles alone, but had to apply judgemental decisions. Finally, and most importantly, the builder had to ensure the structural integrity of the building: “for an honourable work glorifies its master, if it stands up” (ibid.).

To achieve this, masons used a combination of experience and practical geometry. Geometry was a subject taught in universities, but there is no reason to assume that masons took academic degrees (Shelby 1972: 397). Therefore, what they required was a practical form of geometry, that did not presuppose complicated calculations. This is precisely what Lechler was providing for his son. The underlying principle was that a relatively small number of dimensions allowed the builder, through a relatively small number of intermediate steps, to arrive at all the dimensions of the large structure he was commissioned to erect. In other words, one “macro-module” (Shelby&Mark 1979: 117) determined most of the other crucial variables of the church. In Lechler’s Instructions this macro-module was the width of the choir. The choir had to be twice as long as it was wide, while the nave of the church was to be twice as long as the choir. The width of the nave, Lechler suggested, was to be the same as that of the choir, and the aisles of the nave half the width of the choir and nave. The height of the building was equally determined by the basic module (ibid.: 118):

> Item, whoever wants to make a choir and give it the correct height should know more than one height, for there are three heights. The first height is one and a half times the width of the choir in the clear; it should be this high up to the tas-de-charge. The other height should be twice as high as the width of the choir in the clear. The third height is for the choir to be three times as high up to the tas-de-charge as its [i.e. the choir’s] width in the clear

Other structural were derived from the same basic measurement. The walls of the choir, Lechler recommended, should be a tenth of the width of the choir. The precise ratio, however, also depended on the quality of the stone. With good stone three inches could be subtracted, when the stone was poor three inches had to be added. The thickness of the wall in turn determined the size of the outside buttresses—at least, this is what Lechler’s Instructions suggest, but he is not completely clear about how the two should be related (ibid.: 118-20).

The same principle of modularity[7] was applied for the design of the smaller elements of a building. A booklet by Mathes Roriczer, another German builder active in the second half of the fifteenth century, describes the design of pinnacles in terms similar to those used for the ground-plan of the church as a whole (Shelby 1977: 84-5):

[7] Alternatively, the term “proportional” knowledge has been used, e.g. in Harvey 1972: ch. 5. Radding&Clark 1992: 37, 48 show that the same underlying principle also applied to Romanesque building.

> If you want to draw a base plan for a pinnacle, according to the masons' technique [derived] out of correct geometry, then begin by making a square a shown hereafter with the letters *a b c d*, so that it is the same distance from *a* to *b* as from *b* to *d*, *d* to *c*, and *c* to *a*, as in the figure drawn hereafter. Then make the square equal in size to the preceding; divide [the distance] from *a* to *b* into two equal parts, and mark an *e* [at the midpoint]. Do the same from *b* to *d* and mark an *h*; from *d* to *c* and mark an *f*; from *c* to *a* and mark a *g*. Then draw lines from *e* to *h*, *h* to *g*, and *g* to *e*, as in the example of the figure drawn hereafter.

By drawing squares within squares according to fixed patterns, the mason could derive a pinnacle from a basic measurement, without any understanding whatsoever of the mathematical principles. In the same way, Roriczer provided his readers with a simplified procedure to measure the length of the circumvention of a circle (ibid.: 121):

> If anyone wishes to make a circular line straight, so that the straight line and the circular are the same length, then make three circles next to one another, and divide [the diameter of] the first circle into seven equal parts, with the letters designated *h a b c d e f g*. Then as far as it is from *h* to *a*, set a point behind [*h*], and mark an *i* there. Then as far as it is from *I* to *k*, equally as long in its circularity is the circular line of one of the three [circles] which stand next to each other…

For the design of vaults, even where their patterning might seem very complicated at first sight, the same modular principles applied. The ground-plan of the nave and choir were sub-divided into a series of rectangles, of which the central point was then easy to establish. Having set out these measurements in real-life size, the builder could then establish with a compass the curvature the "principal arch" (*Prinzipalbogen*) connecting the four corners of the rectangle and the central point. From this `principal arch' the smaller arches making up the vault were then derived, again using proportional measurements (Shelby&Mark 1979: 124-26).

Unfortunately, although perhaps predictably, there was more than one of these systems in use at the time. This is thrown into sharp relief by two debates, organised by the commissioners of the cathedral in Milan, who were insecure about both the aesthetics and the construction of their expensive project. In May 1392 experts from Lombardy met Heinrich Parler, from Gmünd in Germany, to discuss the issues—and failed to agree on the best way forward. Likewise, a similar debate in January 1400 between builders from Lombardy and Jean Mignot, a French architect brought in by the Duke, failed to reach a compromise. Their exchanges, faithfully recorded by the cathedral administrators, point to the clash of two different sets of design principles: both modular, but with different proportions. Mignot was convinced that the Italian system was aesthetically imperfect and construction-wise unsound, but his opponents were unwilling to accept his opinions, and in the end had their way (Ackerman 1949).

It is worth emphasising that the sources hardly ever suggest that there were any religious or cosmic principles behind these procedures.[8] On the contrary, they keep referring to building experience as the guiding light. This also implied that the rules were not set in stone, but should be applied in combination with the common sense, based on experience, of the builder. As Lechler wrote to his son: "Give to this writing careful attention, just as I have written it for you. However, it is not written in such a way that you should follow it in all things. For [in] whatever seems to you that it can be better, then it is better, according to your own good thinking" (Shelby&Mark 1979: 115).

Architectural drawings as we now understand them, were hardly used prior to the fifteenth, or even sixteenth century, and when they survive they show details, like towers or a chapel, rather than the building as a whole (Pacey 2007: 59).[9] When the chapel for King's College, Cambridge was commissioned by Henry VI in 1448, its principal dimensions were simply outlined (Salzman 1967: 520):

> And as touchyng the dimensions of the chirche of my said College of oure lady and saint Nicholas of Cambridge, I have deuised and appointed that the same chirch shal conteyne in lengthe ciiij^{xx}viiij fete of assye without any yles and alle of the widenesse of xl fete and the lengthe of the same chirch from the West ende unto the Auters ate queries dore, shal conteyne cxx fete, etc.

There was, however, no plan.[10] It is possible—even though precious few survive—that the general plan of the building was sketched on a piece of paper, or parchment, but they were anyway no more than a rough guide to the building that was eventually to emerge. The outlay of Soissons cathedral, for example, underwent at least six major revisions during a fifty-year period (James 1989: 119, 198). The design for the cathedral in Milan was changed radically on several occasions during the construction process (Ackerman 1949: 89-90, 103). A legal document from 1340, with the detailed design for a huge palace to be erected across the

[8] This is a contested point; for the opposite interpretation see Hiscock 2007; also Ball 2008: ch. 5.
[9] Wooden models likewise seem to appear only in the 16th century (Meischke 1988: 163).
[10] Radding&Clark 1992: ch. 7 argue that there was a single individual who designed the whole building, but fail to address the implications of the fact that the execution of that design took many generations and was thus subject to numerous personnel changes among the builders in charge of the project.

Campo opposite the Palazzo Pubblico in Siena, leaves substantial leeway for both the patron ("as messer Gontiero may wish") and the builders ("in whichever way is best") (Toker 1985: 79). The architectural "notation" was simply insufficient at the time, to permit builders to work exclusively on the basis of drawings; this would only become possible from the middle of the sixteenth century (ibid.: 88). The basic dimensions of the ground-plan were, instead, set out on the building site, while the various elements of the elevation were drawn, in real-life size, on the floor of the building lodge, preferably in the attic so as to be protected from the wear and tear of the downstairs floor (Pacey 2007). The main instruments used by the master mason for his design work were a ruler, square, and a pair of compasses (Shelby 1961). However, to translate the design into actual building work, another device was used: the template.

Given the patchiness of the general design, much depended on the specific interventions of the builders during the building process itself. As we have seen, this was usually a discontinuous process in which low levels of activity were punctuated by short, intense campaigns. Careful examination of more than one thousand churches in the Parisian basin, all built during the Gothic period, demonstrates how each group of builders imposed their own specific solutions to the parts they were responsible for. Churches which at first sight suggest unity of design, in fact display all kinds of "junctions", marking the end of one campaign and the start of another (James 1989: ch's 2 and 7).

The reason for these junctures seems to have been that each group of builders used their own template. James (1989) goes so far to call those people usually portrayed as the churches' "architects", the "template-makers". Templates were used to guide the stone-cutters' work. Templates were made of wood, and there must have been many identical templates to allow groups of stone-cutters to work simultaneously on similar elements of the building. Because of the huge weights involved, and given the characteristics of the lime mortar which was used to keep the stones together, the various elements—particularly of the vault structures—had to be executed with great precision. Fault margins above one millimetre could have fatal consequences for the stability of the vault's construction (ibid.: 86). Rigorous quality controls of stone-cutter's work were imposed by insisting that they mark individual pieces with their own distinctive signature (Harvey 1975: 126; Janse&deVries 1991: 50). Templates were therefore the single most important tool of the building process, and a repository of the most significant information about the vital elements of the building (James 1989: 34). Templates were also instrumental for the diffusion of innovations. James' (ibid.: 2, and ch. 6) survey has uncovered a coherent group of buildings in northern France built by a master whose name is not properly identifiable in the sources—and therefore dubbed M1 by James—who made a significant contribution to the design of Gothic windows, executed with the help of his templates. It is important to note that such innovations did not necessarily originate with the great churches, but could just as easily been first tried out on the smaller ones (ibid.: 159).

The building of the great churches in particular, was undertaken in short campaigns, separated by long intervals. These intervals were necessary to re-stock the treasuries of the commissioning institutions, but also to allow the mortar of the construction to set and thus to create stability. During the setting, which might take more than a year, signs of the pressures might appear as cracks in the newly finished work. Cracks would lead to adaptations of the construction, to take the pressure off the vulnerable points (Clark&Mark 1984; Mark 1990: 105).

Although this method seems to have produced satisfactory results in most building projects, the experiment might at time go horrible wrong. The best-known example is the collapse of the vaults in Beauvais cathedral, in 1284, and the collapse of its tower in 1573. The tower probably collapsed because of the absence of the as yet un-built nave, which should have provided lateral support for the tower. The first accident has been interpreted as the result of the builders overstepping the mark of what was feasible in stone at the time. It is, however, much more likely that a design error was to blame. Although the vertical structures had initially supported the vaults, under wind pressure deformations were likely to occur that would undermine the integrity of the structure. The present building shows clear signs of reinforcement of precisely those areas that laboratory tests have shown to be most at risk (Wolfe&Mark 1976). Some construction failures only came to light much later. In 1674 the nave of Utrecht Cathedral collapsed, as a result of a hurricane according to contemporaries, but probably also due to construction weaknesses.

Both the organisation of the workforce and the evidence related to the organisation of knowledge seem to point in the same direction. The building of churches was a “messy” process (James 1982: ch. 2). It was conduct as a full-scale experiment; the building site was a “laboratory”, where builders applied their “local and tacit knowledge” (Turnbull 1993: 316-17). This requires us to think about how such knowledge may have been acquired.

4. Training

Like many other pre-industrial products, the various building trades made huge demands on the skills of their producers. Cognitive psychologists have discovered that the time of training required to master complicated skills is in fact remarkably similar across a wide variety of tasks: it takes roughly ten years to become a top-level expert in any kind of skill-based task (Ericsson 1996: 10-11). Obviously, one does not have to go through the whole curriculum to be able to execute certain aspects of a job at a reasonable level. Therefore, the training of skills is usually subdivided into a number of stages. At each point some students will feel they have developed the skills they are looking for, while at the same time it is well-understood that there are further levels of expertise they are forsaking. One reason why it took—and, in fact, still takes—so long for adolescents and young adults to become fully trained, is that crafts typically combine so-called propositional and tacit types of knowledge (Epstein 2004: 383).

Because it cannot be articulated—"we can know more than we can tell", as one scholar put it—tacit knowledge needs to be transferred from person to person (Polanyi 1966: 4). This is confirmed by psychological research that demonstrates how this transfer of tacit knowledge happens most effectively in "communities of practice"; modern skills training programmes in fact still reflect this (Cianciolo et al. 2006: 623-24). It is therefore of the utmost importance that we not only pay attention to the contents of skills education, but at the same time to its social organisation. Before we look at training programmes, however, we must look at two other potential sources of information on building: the clergy, in their capacity as patrons of the buildings, and written documentation.

For a long time it has been thought that the original impulse for the Gothic style—in other words of its innovative design—came from the church itself. There were two good reasons for this assumption. The clergy were the learned class in medieval society, and surely the beauty of the Gothic style should have been inspired by faith and knowledge, two forms of human capital that were uniquely concentrated in the hands of clergymen. This assumption seemed to be confirmed in some of the great architectural documents of the period, the writings of Suger, abbot of Saint-Denis at the time when it obtained a new choir that is often portrayed as the start of the Gothic style. It is, however, not so evident at all what Suger´s precise role was in the designing process, and even if he suggested the general direction at all. There is no eveidence that he had any specific ideas on how to execute such plans.[11]

Written documentation about building and related crafts is in fact extremely rare before the sixteenth century. The famous Villard de Honnecourt, author—perhaps rather compiler—of a famous manuscript on French Gothic cathedrals dating from around 1230, was possibly not a builder himself; at least there is no evidence that he was ever involved in the creation of a building. His drawings have been made either after the building as it was executed, or from extant plans that he may have observed on site (Branner 1963: 137 ff.; Wilson 2000: 141). It is only in the later decades of the fifteenth century that the first building \`manuals´ start to appear. Several small books from Germany survive with detailed instructions for the design and execution of major building works. We have already discussed their contents in the previous sections (Shelby 1977; Shelby&Mark 1979). During the sixteenth century similar guides for carpenters were published. These contained the same practical types of calculations found in stone masons' manuals, i.e. mathematics without the theory, because carpenters could not be assumed to know how to multiply (Yeomans 19&&: 14).

If neither learned institutions like the church, nor written documentation were much of a help to builders, we must obviously look for alternative sources of information that they could tap into. The first one was the family. There are several dynasties of architects, the best-known of which are perhaps the Parler, who were active in Central Europe in the fourteenth and fifteenth centuries. Their last name was derived from the word for building lodge foreman: *parlier*. Their activities are first recorded in Cologne and Gmünd in Central and Southern Germany, where Heinrich Parler was active around the middle of the fourteenth century. The portrait of his son Peter Parler, the most famous of the family, is incorporated in the structure of Prague cathedral, where he was in charge of construction work in the second half of the fourteenth century. Two of his brothers were working as stone masons in Prague and Freiburg, and in Basel. Peter's sons Wenzel and Johann succeeded him as Master of the cathedral works in Prague, Wenzel also worked in Vienna. Their cousin Michael was Master in Strasbourg, while Johann's son, another Johann, worked as stone mason in Prague (Schock-Werner 1978a).

[11] Radding&Clark 1992 proposes a more elegant solution, pointing to parallel changes in philosophy and building style in the Paris basin in the first half of the 12th century as an expression of similar intellectual developments, but without claiming a direct impact from one upon the other.

Other names repeatedly found in the accounts of the building lodges in southern Germany are Ensingen, Böblinger, Prachatitzes, and also Roriczer (or Roritzer); from the latter family we already met Mathes Roriczer as the author of an instruction manual. Four members of the Roriczer family in three successive generations held the office of cathedral architect at the building lodge in Regensburg. Mathes' grandfather Wenzel was in office from 1415-19. His widow married another stone mason, Andreas Engel, who also took up the office, and was succeeded by his stepson Conrad Roriczer in 1456. Conrad was in turn succeeded, around 1480, by his son Mathes. Conrad in 1463 "made his son a master", suggesting that he had educated him in the business. Mathes' career first took him to Nurnberg, and he was also active in Eichstätt, before returning to Regensburg. Conrad himself had also at some point worked in Nurnberg and Eichstätt, as well as in Ingolstadt and Nördlingen (Shelby 1977: 7-28).

In the Low Countries we see the same pattern of successive generations of stone masons undertaking large building projects over a wide area. Of the Keldermans family, a total of seven generations are known to have been active as builders. Jan Keldermans, who lived in Brussels, was working in Malines during the 1370 and '80s. His son Jan was admitted to the Brussels Stone Masons guild in 1399; he too worked in Malines, as well as in Louvain and Lier. He died in 1445. The following generations expanded the scope of the business to the northern Netherlands, including places like Haarlem, Middelburg, Veere, Utrecht, and even as far away as Alkmaar. In the early sixteenth century they moved the business' headquarters to Antwerp, where it seems to have petered out in the middle of the century (Wylick-Westermann 1987). Between the mid-fifteenth and the mid-seventeenth centuries, the Van Neurenberg family were equally active as the designers and executers of a great many public building projects throughout the Low Countries. Originating from the Namur region in Belgium, the first traces of the family in the northern Netherlands are found in the accounts of Utrecht cathedral, where one Willem van Noerenberch worked side by side with Andries Keldermans. Later they were mainly active in Maastricht, as well as in Dinant, before moving north again (Tussenbroek 2006). Both the Keldermans and Van Neurenberg families were at one and the same time active as dealers in stone and builders in their own right. Obviously, first-hand knowledge of the material and of its application were acquired simultaneously in these families.

This, however, cannot have been true for all workers in the industry; data from a later period, at least, point in exactly the opposite direction. Of eighty apprentice bricklayers in York between 1654 and 1752 whose fathers' occupation is known, only 21 were also bricklayers (and 11 of them apprenticed their son). In other words, three-quarters cam from outside the trade. If we take into account that the likelihood was that there were very few bricklayers' sons among the over 200 apprentice bricklayers during that same period whose fathers' occupations were unknown, it seems not unlikely that ultimately less than ten percent were actually continuing their fathers' trade (Woodward 1995: 54-55).[12] Many, possibly the great majority, of builders, must have learned the tricks of their trade in another environment. Three settings have already suggested themselves in the course of the previous discussion: the stone quarry, the building lodge, and the local guild.

The actual work in the quarries has so far not been properly investigated, and we can therefore say next to nothing about their contribution to the training of the skilled workforce (cf. Goldthwaite 1980: 218). The names of stonemasons in the Northern Low Countries very often refer to places of origin in the areas where the stone was found, strongly suggesting a close connection between the quarrying, and the acquisition of the skills necessary to work the stone (Janse&De Vries 1991: 25). The division of labour in the quarries, between for instance those who did the rough work, and others charged with finishing stones, or preparing sculpted pieces, must have implied a distinction between various types, or perhaps rather stages, of the stone cutters´ education, but this is already speculation (Harvey 1975: 124).

The building lodge was both a concrete location and an organisational form. In the first sense it consisted of the—temporary or semi-permanent, depending on the circumstances—shelter on the construction site, usually of a church building. Sometimes the lodge was a building in its own right, sometimes it was merely a covered space, protecting the workers against sunshine and rainfall, but without proper walls. The coverage permitted the continuity of at least the cutting and preparation of stones, independent from the weather. It is, however, the building lodge as an organisation that interests us here. Like families and guilds, the building lodge was a hierarchical and regulated institution, headed by one or more *directores fabricae* (Schock-Werner 1978b). The lodge was financed by its patrons, but some had more or less independent sources of income, as in Strasbourg, where the lodge property secured a steady and substantial income stream. In Basel, for instance, the lodge owned a house to accommodate itinerant workers. One of these itinerant workers might indeed be the Master of the works himself; in that case the continuity was the responsibility of his substitute, the *parlier*. Under the Master and the *parlier* worked the journeymen, as well as the apprentices.

[12] This was true in many other trades as well: Epstein&Prak 2008: 9-10.

The hierarchy was meticulously described in statutes drawn up during a meeting of master stonemasons from the Holy Roman Empire in Regensburg in April 1459 (Segers 1980). This meeting had been preceded by similar ones in Speyer and Strasbourg, but the Regensburg meeting produced a set of 83 rules for the craft that were going to be applicable in three huge districts, each under the leadership of its most important building lodge: Cologne, Strasbourg, and Vienna.[13]

The masons' guilds have a somewhat ambiguous role in the history of European church building. The earliest craft guilds were established halfway through the twelfth century (Epstein 1991: ch. 2), i.e. well into the Gothic building boom. Moreover, guilds in the building industry were not among the early foundations. The masons' guild established in Lincoln in 1313 was a religious confraternity, not a craft guild. In London, the first sign of an organisation of the masons dates from 1376, although regulations for the trade had already been introduced a little earlier, in 1356 (Knoop&Jones 1967: 135-36). Clearly, guilds were not a prerequisite for the building industry. Still, they became more important as time went on. In the Italian towns building crafts obtained statutes in the course of the fourteenth century (Goldthwaite 1980: 431-34). With the increase in urbanisation, the demand for building work must have increased to such an extent, that local economies found it easier to sustain a permanent building industry, not just for house building, but also for the construction of larger structures. Even though it remained inevitable to recruit specialist labour from outside of town, many of the routine jobs could be undertaken by locally resident workers, who may also have sustained low-level building activities in between the campaigns of greater intensity. The fact that the "management"—known by name—remained mobile, may have obscured the role of anonymous local craftsmen (Kolman 1993: 110).

This was probably especially true for carpenters, about whom we know otherwise very little. Much of the scaffolding and other carpenting jobs must have been pretty straightforward for craftsmen used to building houses and other complex structures, so there was little need to bypass local expertise. By implication, carpenters working on religious projects were probably trained locally as well. The work in stone and brick must have been a combination of specialised and routine work. Local masons, trained locally by master masons within a guild structure, were available, at least in the larger population centres. In the Hansa town of Kampen, in the Netherlands, the first guild regulation for the carpenters, from 1483,

[13] The regulations thus covered the area of stone building; in the "brick"-regions of the North there were not enough stone masons to allow complex institutions (Segers 1980: 1).

discusses apprenticeship. These same regulations also contained special clauses for masters who undertook large building projects (ibid.: 114). Carpenters' names, where known, suggest local origin, in contrast with those of stonemasons (Janse&De Vries 1991:25).

Guild statutes regulated the training of aspiring workers in the trade, even though the training itself was left to individual masters. Interestingly, the minimum training period varied significantly, even in relatively small areas. In Verona the minimum was just one year, in Piacenza four, in Bologna five, in Genoa and Savona six years, and in Venice six to seven years. The statutes in Padua distinguish between stonecutters, who are required to learn for six years, and the wallers, whose apprenticeship takes up eight years (Goldthwaite 1980: 260).[14] Clearly, these regulations are referring to very different levels of accomplishment and suggest that five to six years were required at least to become fully competent, while it is very likely that additional experience was necessary before admission as an independent master (Epstein&Prak 2008: 8). This seems to be confirmed by the regulations for Parisian masons from the mid-thirteenth century, a document full of references to the skills of the master (quoted from Binding 1993: 104-05):

> In Paris everyone can be a mason, provided he knows the trade (*le mestier*) and works according to the customs and practices of the trade, which are as follows: Only those who have been apprenticed can work in a workshop, and after his apprenticeship he can exercise the trade independently only after six years of experience… The mason can employ journeymen from among the apprentices in their fifth year, provided this is not the first journeyman.

A similar interest in training can be found in the rules drafted by the meeting of master stonemasons from the Holy Roman Empire in Regensburg in 1459. The regulations are interesting for a variety of reasons, but we will concentrate here on the training aspects. These were covered by a special section on the *dienner*, or apprentices (ibid., 179-80). Stone masons were required to train for six years; wallers were supposed to be qualified after four years. On top of that, apprentices should gain experience for another year, while they were moving around. Before accepting an apprentice, the master should verify his family background; only boys whose parents were legally married and of good reputation, were acceptable in the trade. Various articles regulated the incomplete apprenticeship. Apprentices who interrupted their training without good reason should not be able to continue under another master, and likewise masters could not poach each others' apprentices. More generally, the most

[14] In Germany it was the other way around: wallers had to be apprenticed for four years, stonemasons for six (Segers 1980: &&).

important aim of the regulations seems to have been the continuous supply of qualified labour. The regulations were recommended to local workshops, but could not be enforced because the Regensburg meeting had no legal status. Many of their rules were, however, adapted by local institutions or voluntarily adhered to by stone masons in the following centuries.

We thus see a range of institutions offering opportunities for the acquisition of skills. It would, however, be wrong to see these institutions as opposites. Quite the contrary, the available evidence suggests institutions existing side by side, working out their relations in local settings according to the particularities of these settings (Schock-Werner 1978c). Neither the family, nor the quarry, or the building lodge, and not even the guild, provided a full-fledged training programme. What these institutions did provide, was an environment with educational potential. Among these, the guilds were most articulate in their interests in the training of the workforce. As the guilds over time seem to have become more significant in the regulation of the building trade, training, by implication, became a more important concern for the industry as a whole.

5. Building in brick

In regions with a good supply of building stone (ashlar), this was the raw material of choice, for buildings generally, and for large, prestigious constructions in particular. In England, for example, we find brick elements, but hardly any complete brick buildings before the fifteenth century. The brick making industry had almost completely vanished from the British Isles after the Romans had left. (Lloyd 1983: 2-5). In some regions, such as the northern Netherlands, stone could be imported thanks to a helpful waterway system that limited the costs of transport. But still other regions were not so fortunate and effectively closed off from sufficient supplies of stone. In Europe this was particularly true in the Baltic. Builders there were forced to work with brick. This is significant in world historical perspective, because brick was utilised for large constructions in many other parts of Eurasia as well.

Brick had been popular as a building material already with the Romans.[15] Many of the surviving constructions in Rome itself, are built in brick, although sometimes covered with

[15] General works on brick building, with guides to further reading, include Campbell&Pryce 2003, and Turner 1983: 767-97.

stone (marble) facades. The construction properties of brick are not fundamentally different from those of stone, and due to their uniformity bricks have some distinct advantages (Mark 1995: 9). Nonetheless, it took quite some time before the brick making industry revived; during much of the Middle Ages, brick went out of fashion on the north side of the Alps where Roman bricks were simply re-utilised if there was a demand for bricks at all. In the Baltic area the revival only happened in the twelfth century (Böker 1988: 6), and it was not before the second half of the thirteenth that builders first created Gothic brick churches in the region, over one hundred years after the creation of Gothic in France (Nussbaum 2000: 77).

The use of brick created a specific variety of the Gothic style in *Backsteingotik*, or brick Gothic. The small size of bricks allows lively surface patterns, but not quite the same varied decorations as are possible in stone. As a result, *Backsteingotik* produced “calm, homogeneous surface values and sharp, block-like contours” (ibid.). This latter impression was reinforced by a preference for the hall-type of design, where the nave and the side aisles are all under the same roof, creating a more bulky impression than the French designs. Nonetheless, northern German masons, and their colleagues working in Poland and Scandinavia, proved themselves masters of intricate patterning; the first stellar vaults, for instance, were created in a *Backsteingotik* church for the Cistercian monastery of Pelplin, not far from Gdansk, in the late thirteenth century (ibid.: 83-84). They were also capable of impressive engineering feats, including Gdansk’s St. Mary, the largest brick church in the world.

Brick technology was capable of even more remarkable engineering, most notably in Brunelleschi’s dome for the cathedral in Florence. The dome, completed in 1446, was constructed with the help of complex patterns of masonry which helped stabilise the shape of the dome during the construction itself. Brunelleschi employed a technique also used by builders in Iran, and it is possible that he was informed about it through trade contacts between Italy and the Middle East. However, his dome is much larger than contemporary Persian constructions, and the engineering problems were likewise more challenging. He managed to solve them with the help of brick, because bricks are both lighter, thus reducing the pressures on the construction, and smaller. The small size allowed the masons to create herringbone patterns in which the weight of the dome pushed the bricks more firmly into their places (Campbell&Pryce 2003: 126-27). Brick, in other words, may have been a second-rate choice in terms of prestige, but from an engineering point of view it provided builders with a quality material.

II Other regions of Eurasia

6. Byzantium

In the Byzantine Empire the heyday of church building was over by 1000 AD. Hagia Sophia dated from the sixth century and no equivalent church buildings were constructed during the subsequent millennium. Having said that, a great many new churches were created in the revival following the Iconoclast Controversy, which ended in 843. Moreover, this period saw the development of a new church lay-out, the so-called cross-in-square church. Contrary to the Latin churches, where the cross shape determines the ground plan of the building, this Byzantine type is almost square, with a cross shape inserted into the interior lay-out (Ousterhout 1999: 12).[16] So, even though less spectacularly than with the Gothic style in the West, the building of the Byzantine empire was equally capable of producing innovations. In contrast with the Latin West, however, brick was the dominant building material in South Eastern Europe and Asia Minor.

The building industry in Byzantium featured characteristics remarkably reminiscent of those we have come across in the Latin West. The people in charge of the design and construction were engineers rather than artists (ibid.: 44). No architectural plans have survived, and traces in extant buildings suggest that whatever drawing was called for, was made full-scale, and on location. Churches were designed and built as "modular units" (ibid.: 58), and designs were changed repeatedly in the course of the construction process (ibid.: 86). The churches were remarkably uniform in general design, suggesting an intensive exchange of information throughout the empire, but at the same time displayed local variations in detailing, which seem to suggest that labour markets for building workers may have been regional rather than national (ibid.: 26, 56-57, 116).

Proportional geometry was the key to the designing of a church. But whereas in the Latin West the choir was the most important element of the building, and hence determined the proportions of its other features, the central "module" in Byzantine churches was the dome. It height therefore acted as the "controlling element" of the design (ibid.: 72, 80-81).

Because of the relative unimportance of stone, quarries were likewise insignificant as locations for training the workforce. The two other environments we identified in the Latin

[16] As will be evident from the references, this section relies entirely on Ousterhout's wonderfully helpful book.

West were, however, equally important for the Byzantine building industry: the workshop and the guild (ibid.: 49-57). Unfortunately, very little is known about the early history of Byzantine guilds, although we do know that they emerged earlier than in the Latin West, and that they continued to function throughout the Middle and Late Byzantine periods. The guilds seem to have enforced quality controls, by holding the master accountable—for brick buildings the warranty extended to a ten year period—and prohibiting him to take on a new project before he finished the current one. They also insisted on proper skills: “Those who build walls and domes or vaults must possess great exactitude and experience lest the foundation prove unsound and the building crooked or uneven”, says the Book of the Eparch, a source from the tenth century listing some regulations concerned with crafts (ibid.: 50). Whereas guilds were permanent institutions, workshops were temporary arrangements, attached to the building project itself. They were headed by a master builder, or master mason, in charge of the work force. Apprentices must have been trained on the job, but the sources are silent on this aspect. As in the West, numbers fluctuated from a handful to several hundred. Not all of them were necessarily skilled; building entailed a lot carrying and lifting that could be left to unskilled helpers. The sources do indicate that the workforce was highly mobile.

6. Iran, Afghanistan, Uzbekistan, Turkmenistan

Very few written sources have survived about the building workers who constructed the Timurid sacred buildings—which are found in what is now northern Iran, Afghanistan, Uzbekistan, and Turkmenistan—but a picture, copied in 872/1467 and now in the Johns Hopkins University library, provides some clues. For one, it shows a variety of handicrafts, including stone cutters, tile makers, brick masons, mortar makers. There is also scaffolding in evidence, suggesting contributions by carpenters. Equally interesting is the variety of ethnic backgrounds of the workmen pictured here, which include people from the region, as well as what look to be people of Mongol and African descent. This suggests the importance of mobility among building workers (Golombek&Wilber 1988 I: 91-92, and II: pl. 481). The variety of crafts is confirmed by a compilation of the names of craftsmen found on a range of Timurid buildings which covers over twenty different crafts; carpenters are among the most numerous with 15 references from a total of 107 craftsmen (ibid. I: 65-66).

Timurid builders used sophisticated geometry, based on “modular” principles (ibid. I: 139). A series of drawings from a sixteenth-century architect of Bukhara—in Uzbekistan—shows various complex buildings set out on modular grids. It seems no single element was consistently used as the basic module, but that the most prominent element was normally picked for this purpose. In the case of religious buildings this was most obviously the dome. The proportional dimensions, which determined the relations between the various elements within an overarching aesthetic, possibly went back to the same source as Vitruvius (ibid. I: 139-40).[17] Craft skills seem to have been transferred principally through the family system (ibid. I: 67).

7. China

It is difficult to say whether Song China (960-1279) experienced a building boom similar to European Gothic, but it is fact that during this period numerous pagodas were erected. These Buddhist buildings could achieve impressive heights. The “Iron Pagoda” of Kaifeng, which is in fact made of iron-grey glazed bricks, reached 57 m, the wooden pagoda of the Fogong temple in Shanxi came to 67 m, and the Liuhe, or Six Harmonies Pagoda in Hangzhou, also built in brick, stands 60 m tall. The tallest still in existence is the Liaodi Pagoda, built in 1055, which come to 84 m (Watson 2000: ch. 5).

Unlike most European towers, the Buddhist pagodas in China were free-standing buildings, without any support from an appended church building (Guo 2005: ch. 5). The buildings therefore have wide-spreading eaves, which help stabilise the construction (Watson 2000: 78). Apart from the usual dangers of fire—the pagoda in Kaifeng was struck by lightning and burned down in 1044—they also had to be able to cope with the problems of high winds and earthquakes (Glahn 1981: 132; Ledderose 2000: 106, 110). For this reason, large structures were often constructed of wooden posts and beams, set on top—but not inserted into—a concrete platform. The curved shape of the roofs helped the wind to skid the structure; the extension of the roofs also protected the wooden frame from the rain. Chinese builders used roof tiles up to four times as heavy as those utilised in Europe, again to stabilise the constructions, i.e. to prevent them from being blown over by the wind. Compared to European cathedrals, the pagodas were built quickly, in less than ten years (Guo 2005: 64).

[17] This modular principle has been uncovered by the Russian architectural historian M.S. Bulatov; see Golombek&Wilber 1988 I: 173.

Chinese art, it has been claimed, is “modular” across the board, because of the particularities of Chinese script; to master the many signs, Chinese have to understand the underlying principles, i.e. the modules which compose the various characters (Ledderose 2000: ch. 1). This is true as well for its architecture (ibid.: ch. 5; also Guo 2005: 93, and Watson 2000: 85). This modularity comes out very clearly in a treatise, completed by Li Jie around 1100, at the end of the reign of Emperor Zhe Zong: the *Yingzao fashi*, or State Building Standards. The *Yingzao fashi* is 1,078 pages long and provides guide-lines for the construction of a variety of public buildings, as well as private homes. It was first printed in 1103.

Li Jie was not himself a builder, but a bureaucrat, as well as a painter, and the author of other books on geography, history and philology. The *Yingzao fashi* was compiled as part of a governmental attempt to regulate a variety of its activities—the so-called Wang Anshi Reform—including the construction of public buildings (Guo 2005: ch. 7). Li worked as Superintendent for State Buildings in the Ministry of Works, and as such had first-hand experience of the building trade. His guidelines reworked an older set of codes, which were no longer deemed adequate, because they did not mention any size variations, nor correct estimates for amounts of material and manpower necessary to create buildings of various sizes.

The first part of the *Yingzao fashi* contains a glossary of various technicalities, mathematical formulae, and building proportions (ibid.: 93-96). The second part discusses standards and regulations for the design and construction, as well as guidelines for the production of brick and tiles. These try to achieve the highest possible amount of standardisation, through technical specification. The third part regulates the work: quality standards, wage expenses depending on the season and the materials utilised. Part four deals with the building materials themselves, whilst part five provides technical drawings showing how the various aspects of the building should be executed. What is especially interesting is that, as in Europe, the mathematics are mostly based on proportions. The *Yingzao fashi* distinguishes eight building sizes and recommends a standard size of the beam for each of them. That beam size—the *cai*—determines the proportions for all the elements used for the complex construction of the roofs and their support structures, as well as other aspects of the building.

It is not so clear if Chinese builders used architectural drawings. The *Yingzao fashi* does provide various types of working drawings, but no others seem to have survived from the medieval period (ibid.: ch. 10). Perhaps the standardised form of building made these superfluous. Many buildings were erected around a courtyard and there are again modular principles are at work (Ledderose 2000: 113-14). The courtyard was, for instance, supposed to be symmetrical. The entrance is through a gate on the southern side, and the main building opposite the gate with an open front. Secondary buildings were located at the western and eastern ends of the courtyard. The Buddhist monastery Chonghansi (Shanxi province) from the late fifteenth century, was laid out as a series of courtyards, and so was the Imperial Palace in Beijing. Interestingly, many architectural clay models have survived in China, although the majority date from the earlier Han Period (206 BCE – 220 CE). Their role in the building process remains, however, elusive (De Bisscop 2007: 53)

Chinese builders were organised in family guilds, registered, regulated and supervised by the government (Guo 2005: 90). Such guilds also existed in other lines of trade. It is not clear to what extent they can be compared to the European guild system (Moll-Murata 2006). One aspect that sets these Chinese guilds apart, was the compulsory transmission of the craft—and by implication its skills—to at least one member of the next generation in each craft family (Guo 2005: 90). Another Chinese peculiarity, it seems, was that building knowledge was transferred orally in verse form, presumably because that made it easier to memorise (ibid.).

As in Europe and Asia Minor, Chinese builders relied on modular knowledge. They were organised in guild-like institutions, regulated by the government.

Conclusions

Three main points seem to stand out in the preceding discussion of human capital formation in the medieval building industry. Firstly, builders' knowledge was practical, and related to their working experience, rather than theoretical. This is probably the least surprising of our conclusions, but it is a point worth making nonetheless, because the other two conclusions follow from it. It is also important because it underscores a point made by Epstein (2000: 7) that it was not technological constraints as such that hampered the pre-modern economy, but the under-utilisation of the available technologies. The knowledge that we described in this paper was already available to the Romans. It was perhaps insufficient to build a steam engine, but the accomplishments of the constructors of medieval religious buildings across Eurasia demonstrate that, despite the limitations of their practical knowledge, they were capable of remarkable progress in the construction of quite complex other types of "machines" (Gimpel 1977).

The second point to emerge from our investigation of the medieval building industry is that modular knowledge substituted for theoretical knowledge. On the basis of their practical experience, builders had worked out how the various modules of a complex structure like a church building, or the tall towers attached to these buildings, could be reduced to a coherent set of proportional dimensions. These dimensions guided the general patterns of their work. At the same time, the details of that work had to be adapted to local circumstances, such as the quality of the surface on which the building was to be constructed, the type of stone available for the construction, and the financial constraints of the project. Therefore, the application of this knowledge was always embedded in the practice of the building process itself. The construction of a large church building was an "experiment", the building site a "laboratory" (Turnbull 1993).

Work in this "laboratory"—and this is our third conclusion—was, almost by definition, collective, and so was the process of acquiring both the propositional and the implicit knowledge of how to build properly. Building a complex structure like a church was therefore a social, as much as a technological challenge. We have seen how the medieval building industry utilised a number of different social institutions to accomplish its remarkable feats: the family, the building lodge, and the guild. We find these three institutions throughout Eurasia as the appropriate environments for construction work. However, the specific mixtures are still something of a mystery, as is the possible implication of those varying mixtures for the development of the industry.

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